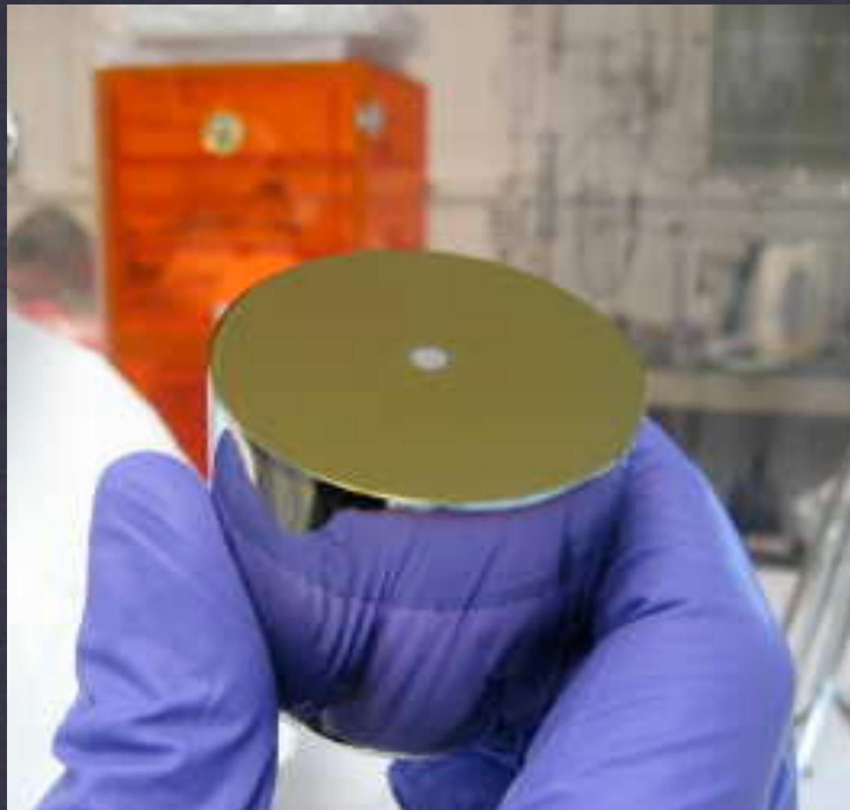
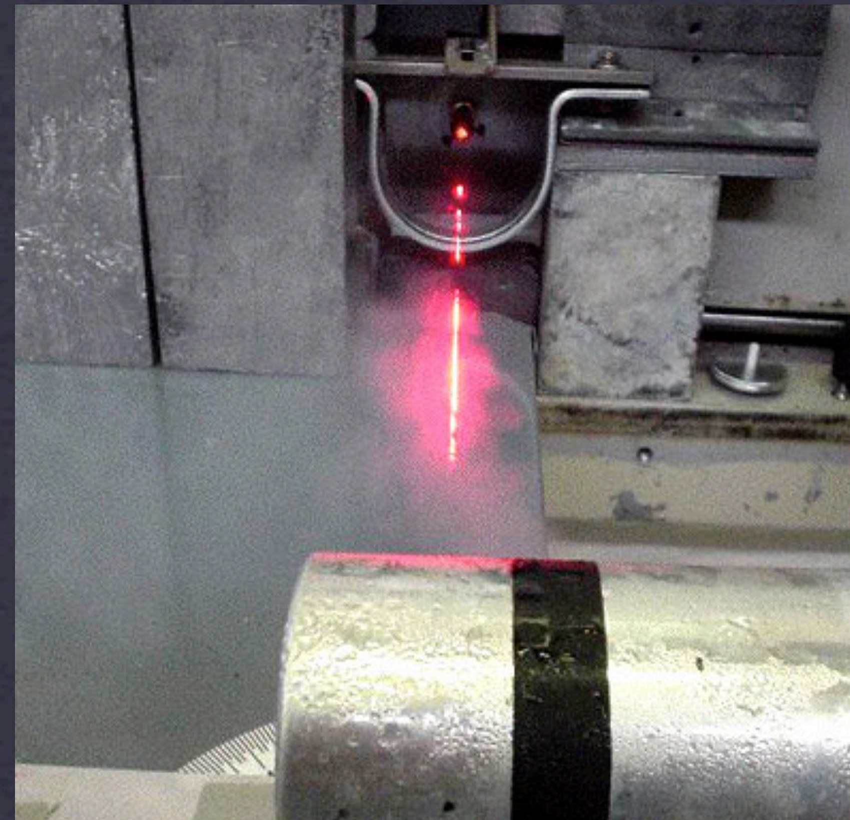
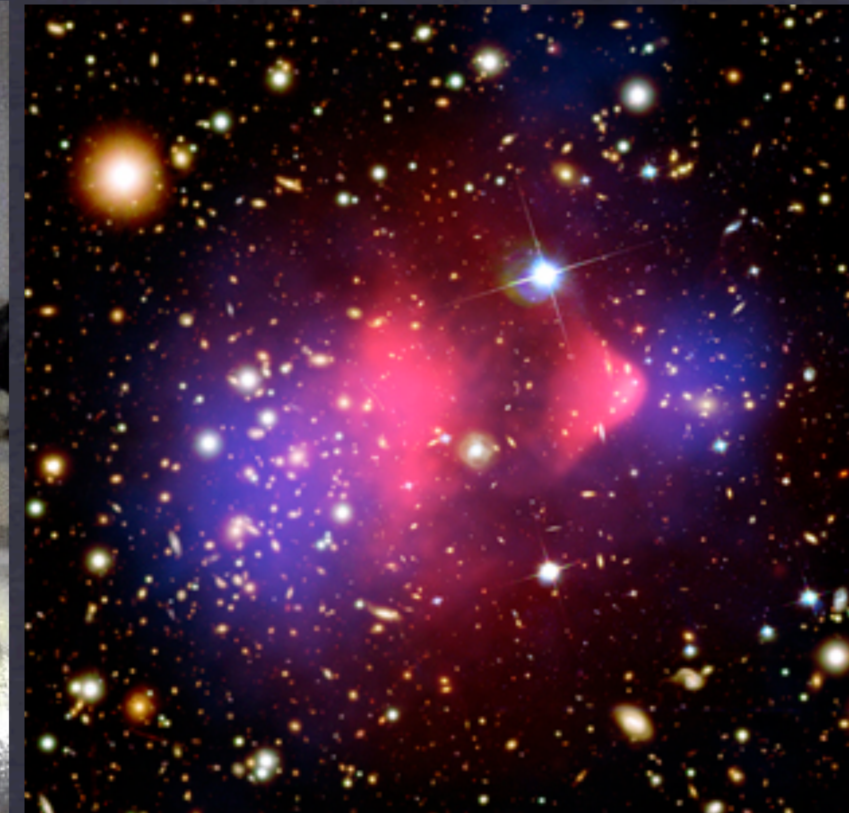
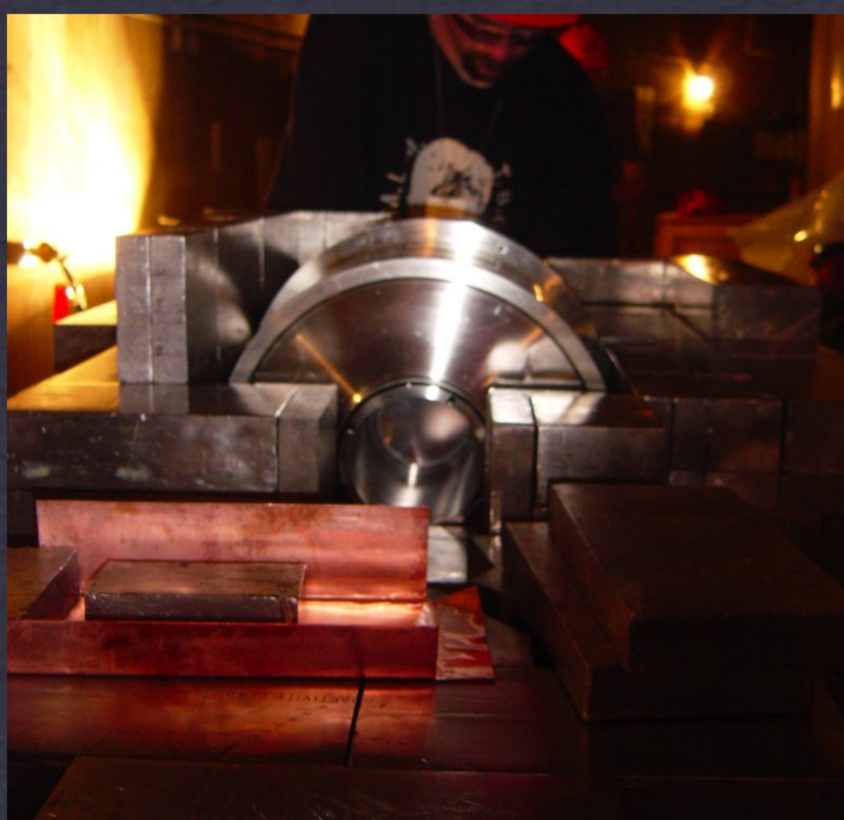
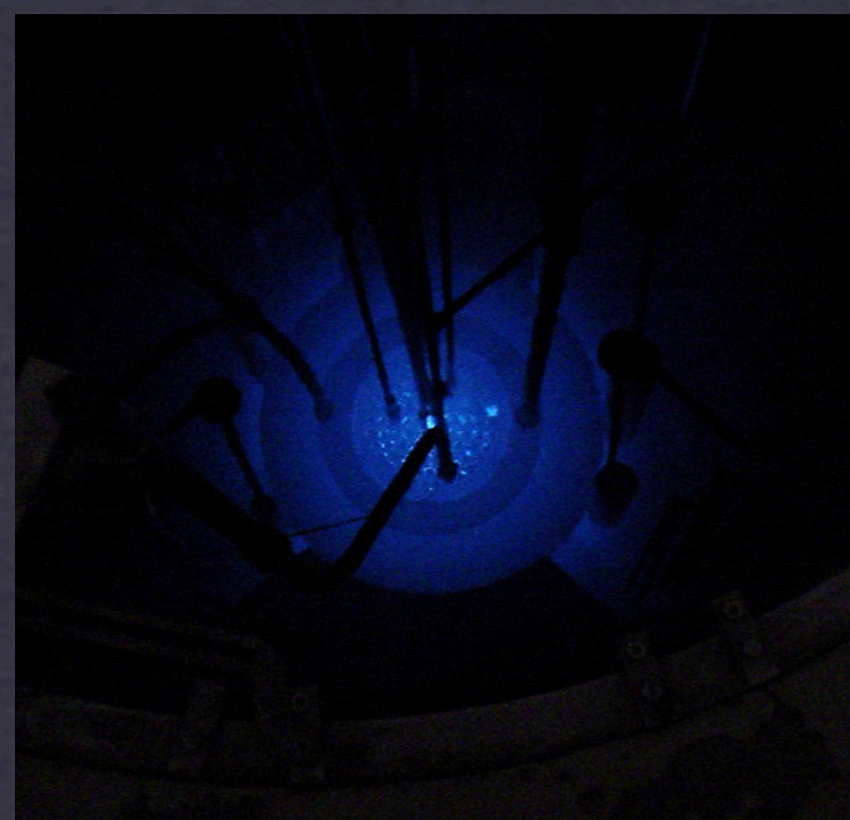







NEUTRINO & DARK MATTER COHERENT INTERACTIONS

NEW AVENUES FOR PRECISION MEASUREMENTS

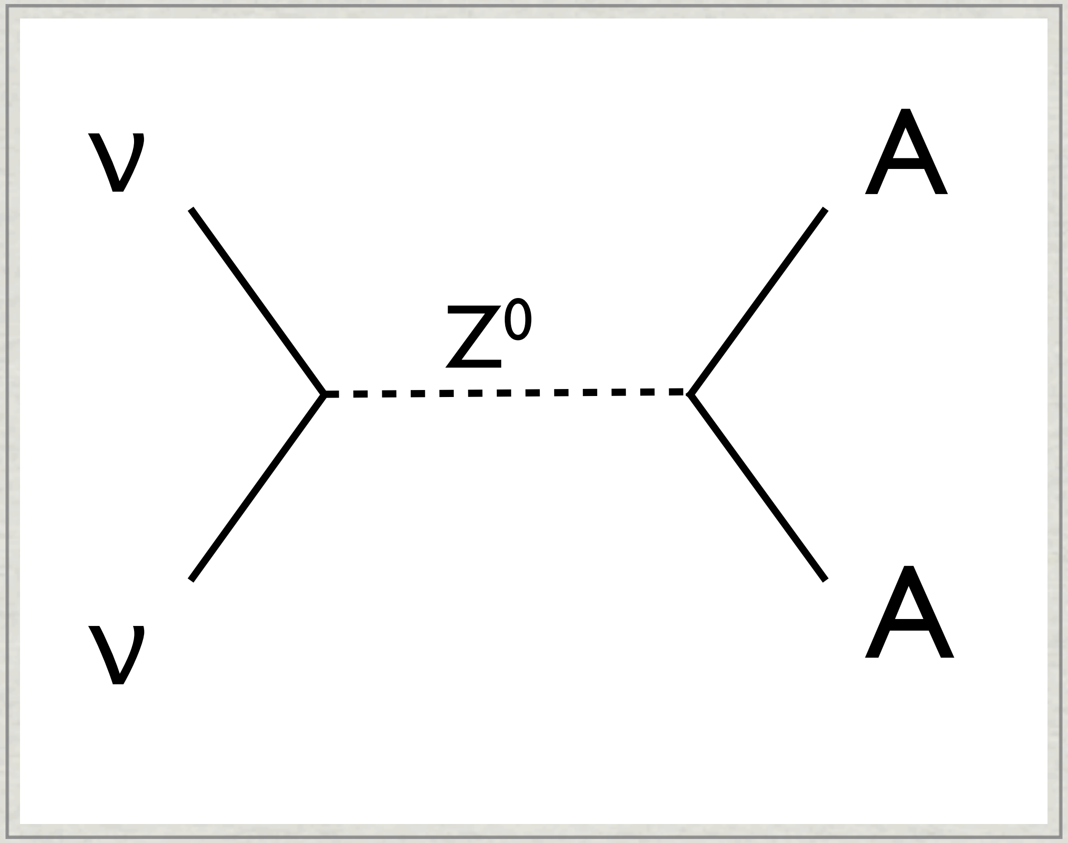
PHIL BARBEAU, STANFORD UNIVERSITY

The Story: Big Physics with Small Detectors

- Coherent Neutrino Scattering
- CoGeNT
- Dark Matter
- New Initiative: MAGν_eT

+ A FEW DIVERSIONS ALONG THE WAY

Coherent ν - Nucleus Scattering



D. Z. Freedman, PRD 9 (5) 1974

- As yet ***unobserved*** Standard Model process: analogous to coherent forward scattering of e+A→e+A. Predicted in 1974 with the realization of the weak neutral current
- Scatters coherently off all nucleons → cross-section enhancement $\sigma \propto N^2$
- Requires identical initial & final nuclear states → neutral current elastic scattering
- Nucleons must recoil <u>in phase</u> → low momentum transfer $qR < 1$→ ***sub-keV recoil***
- E_ν < 10’s of MeV for most nuclei

... in Supernovae

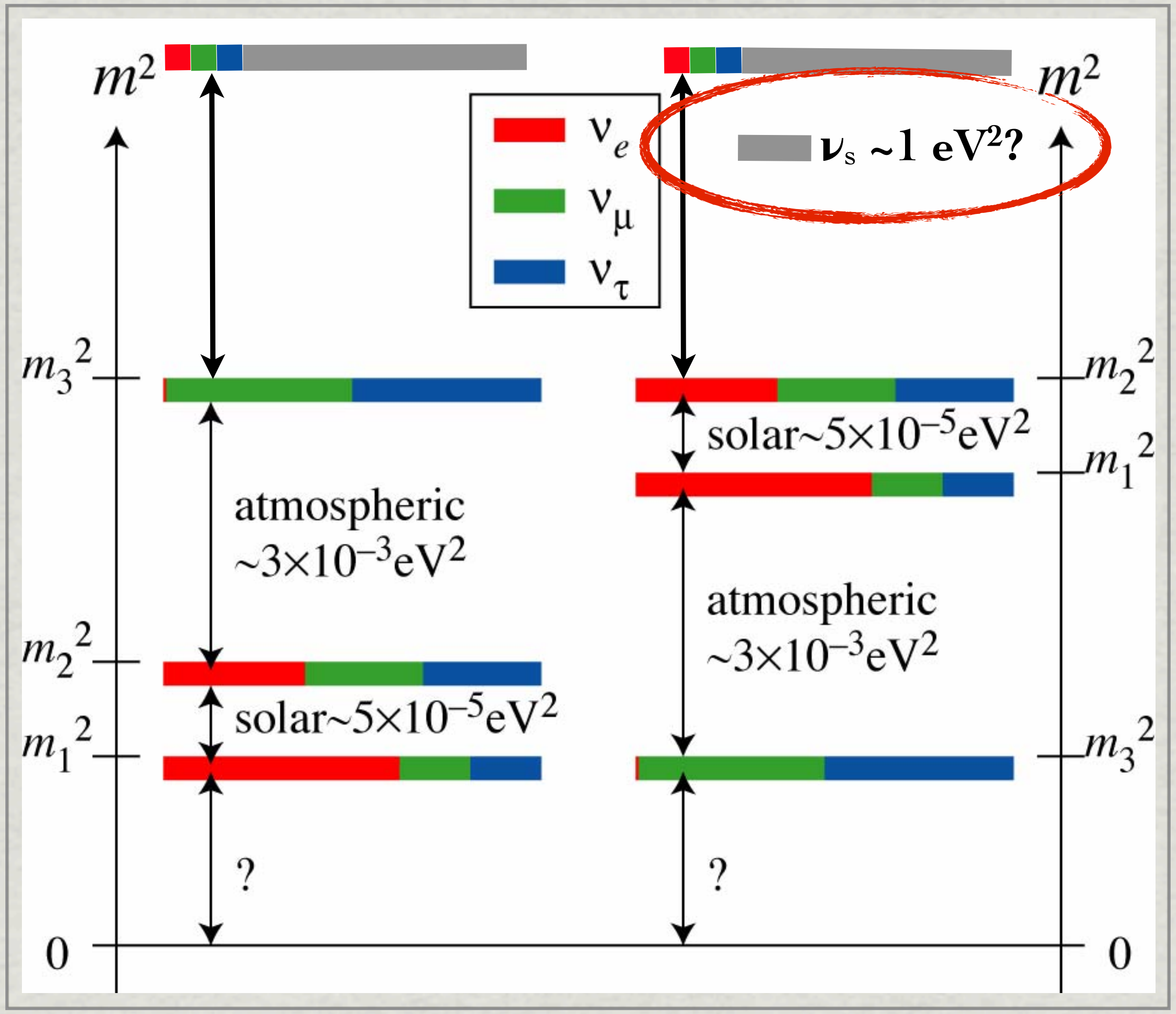
- Largest σ in SN dynamics. Measure to validate models

J.R. Wilson, PRL 32 (74) 849

- A coherent-scatter detector is flavor blind to ν oscillation pattern → measure total E and T of SN

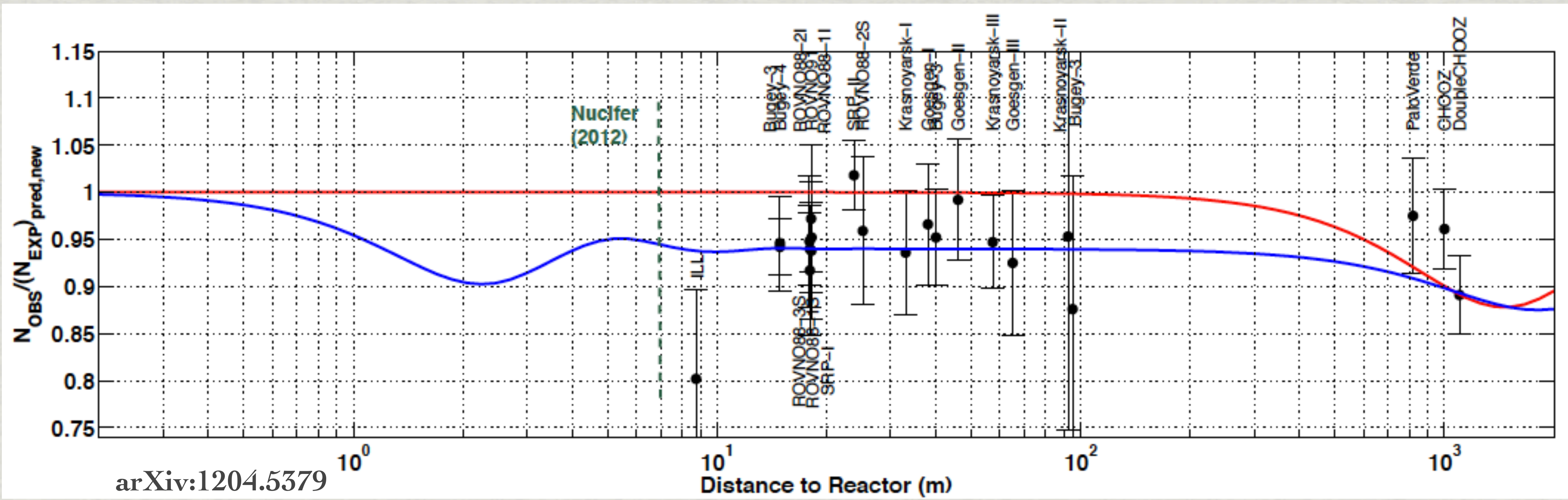
J.F. Beacom, W.M. Far & P. Vogel, PRD 66 (02) 033011

...for sterile ν searches



- ν oscillations → ν's have mass
- 3 ν flavors from Z line width
- ~3 ν flavors from Big Bang Nucleosynthesis

...for sterile ν searches



arXiv:1204.5379

- Short baseline Rx experiments: apparent deficit of anti-ν_e's → possible indication of new physics: $\nu_{sterile}$'s with $\Delta m^2 \sim 1$ eV^2 or Rx flux uncertainties
- A short baseline **neutral current** experiment can help resolve this **"Reactor Anomaly"**

A. Drukier & L. Stodolsky, PRD 30 (84) 2295
C. Giunti and M. Laveder, arXiv:1109.4033 (2011)

...for tests of the Weak Nuclear Charge

- Coherent cross-section proportional to Q_W^2
- A precision measurement of the coherent scattering cross section is a sensitive test of radiative corrections due to new physics above the weak scale (**Technicolor, Z'**, etc.)

$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ \underline{sin^2\theta_w} - 1) + N)^2$$

L. M. Krauss, PLB 269, 407

...non-standard ν interactions (NSI)

- A precision measurement of the coherent cross-section tests for non-universal or flavor-changing NSI (**Supersymmetry, ν mass models**)
- Use multiple nuclear targets

K. Scholberg, Phys.Rev.D73:033005,2006

J. Barranco et al., JHEP0512:021,2005

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi}((G_V + G_A)^2 + (G_V - G_A)^2(1 - \frac{T}{E_\nu})^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2})$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

$$G_A = ((g_a^p + 2\epsilon_{ee}^{uA} + \epsilon_{ee}^{dA})(Z_+ - Z_-) + (g_a^n + \epsilon_{ee}^{uA} + 2\epsilon_{ee}^{dA})(N_+ - N_-))F_{nucl}^A(Q^2)$$

...for ν magnetic moment searches

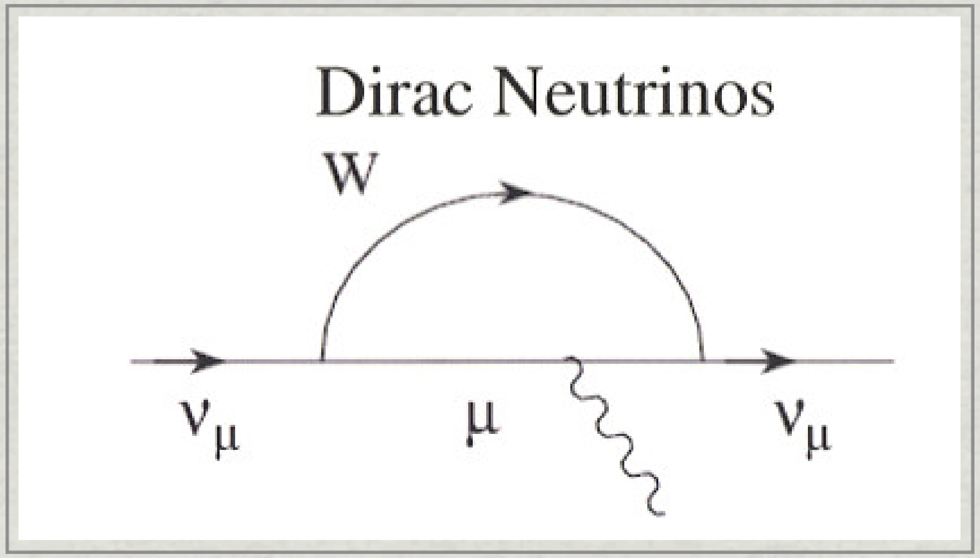
- Massive ν's → small Dirac μ_ν's

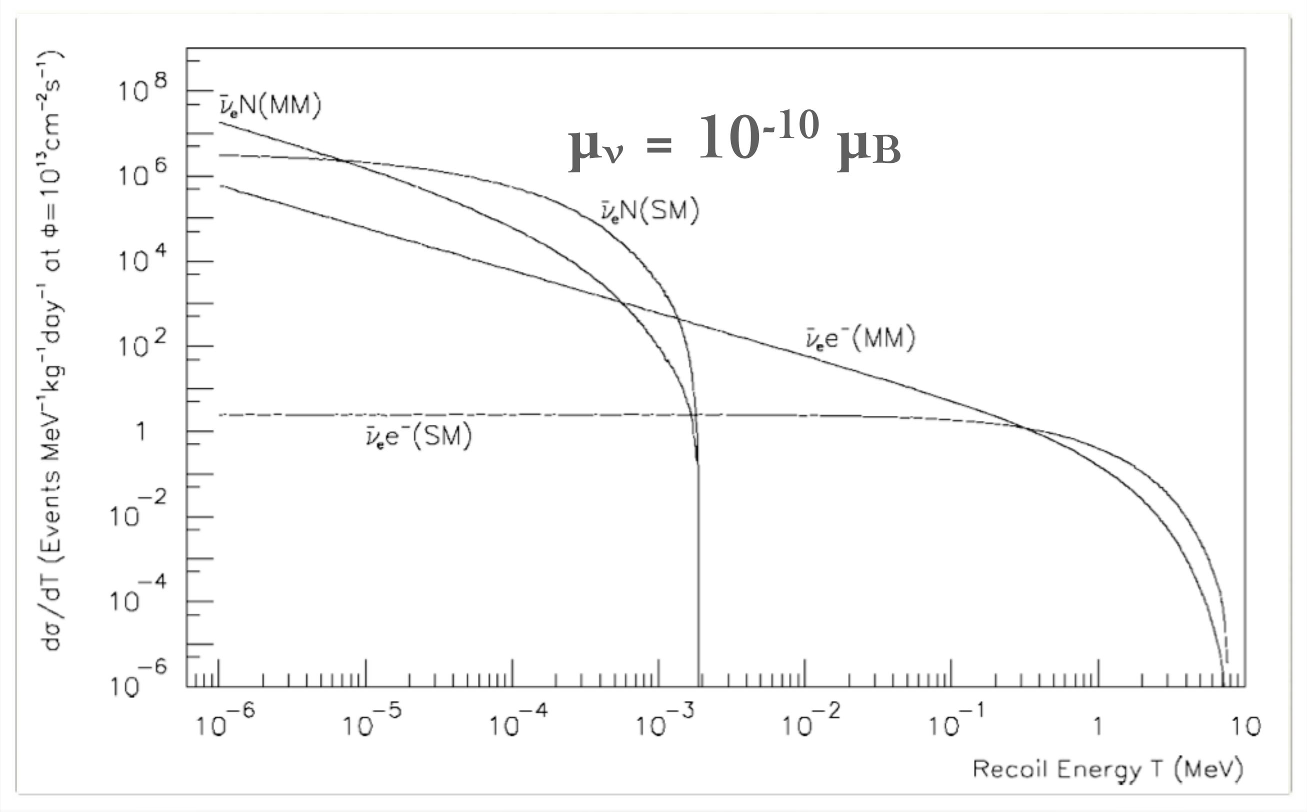
$$\mu_\nu \sim 3 \times 10^{-19} \mu_B \frac{m_\nu}{1\ eV}$$

- Some **Supersymmetric models**, models with **Large Extra Dimensions**, **right-handed weak currents** and **Majorana transition moments** can give rise to (detectable) μ_ν's orders of magnitude larger

- Low threshold detector → high sensitivity (ν-e and coherent ν-nucleus channels)

A. C. Dodd, et al., PLB 266 (91), 434





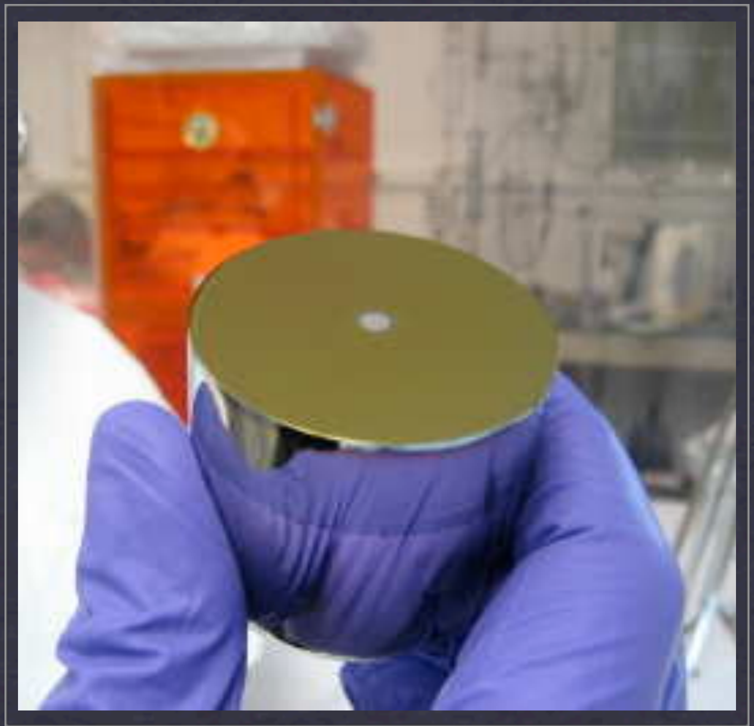
H. T. Wong and H.-B. Li. Mod. Phys. Lett., A20:1103–1117, 2005.

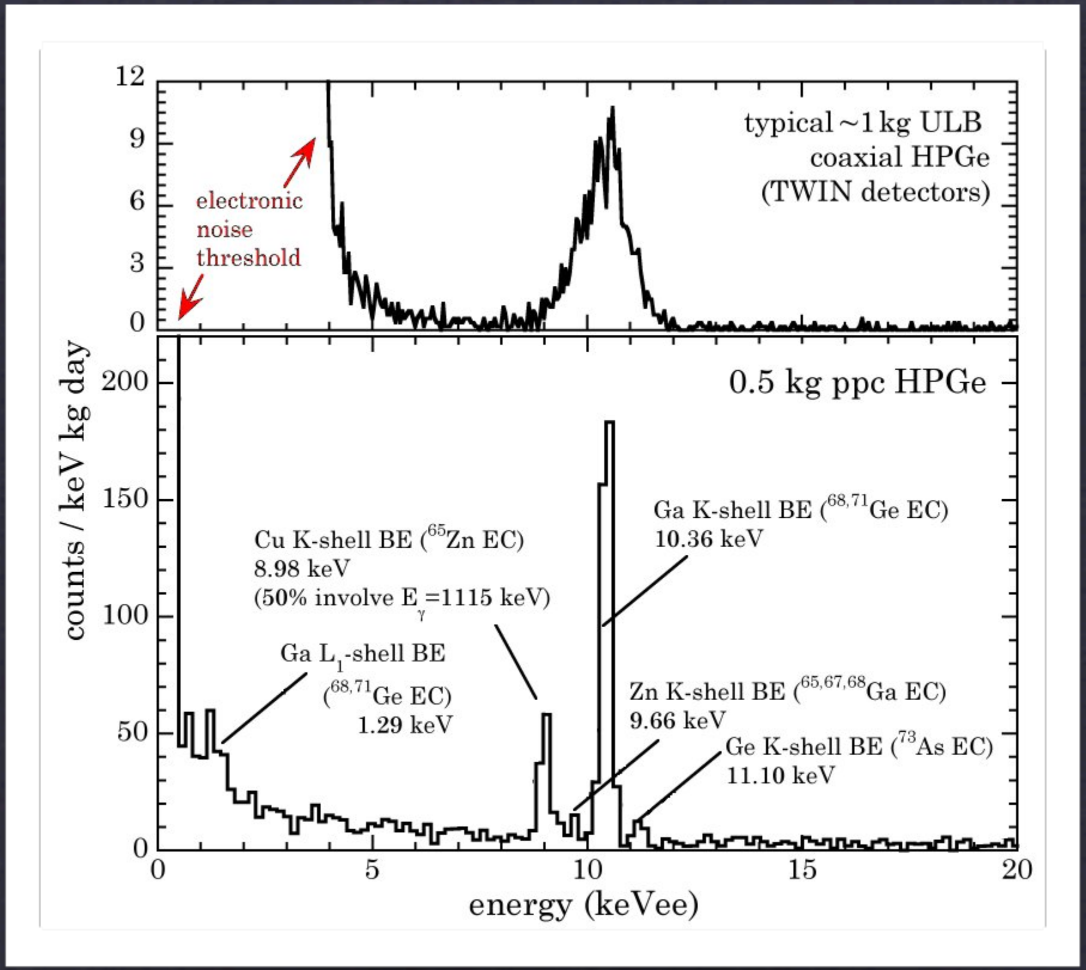
Coherent Germanium Neutrino Technology (CoGeNT)

-Program to develop kg-scale, low background ($c\ keV^{-1}\ kg^{-1}\ d^{-1}$) detectors sensitive to sub-keV nuclear recoils

-Result: P-Type Point Contact HPGe detectors
  0.5 keV threshold & 0.4-1.2 kg

-Take it to a nuclear power reactor (~10^{13} ν's $cm^{-1}\ s^{-1}$)

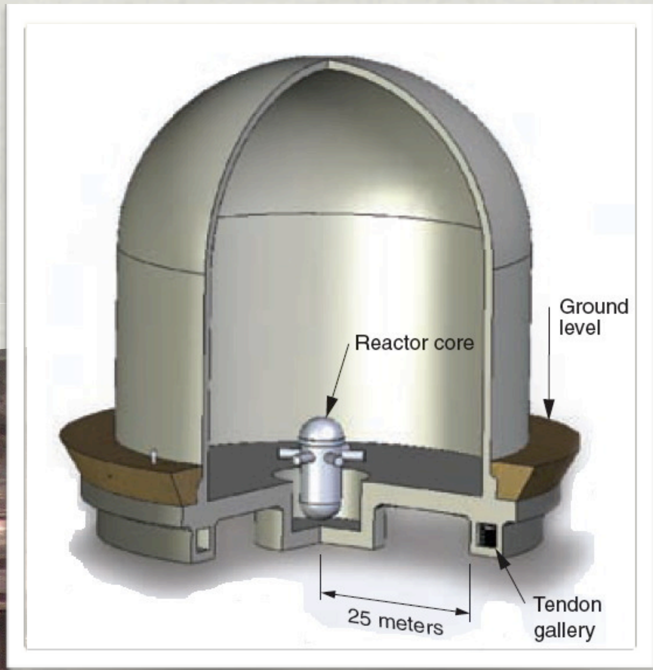


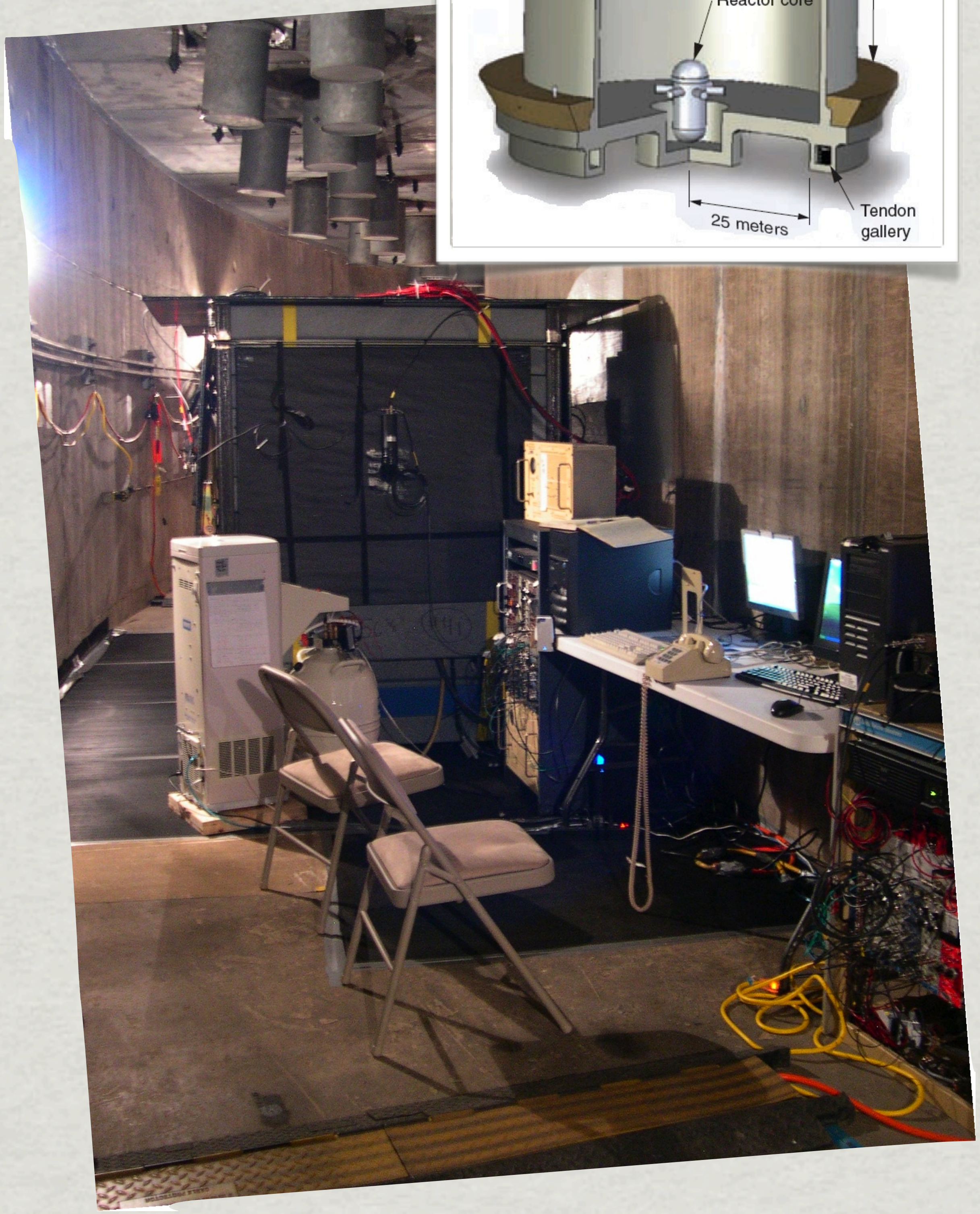


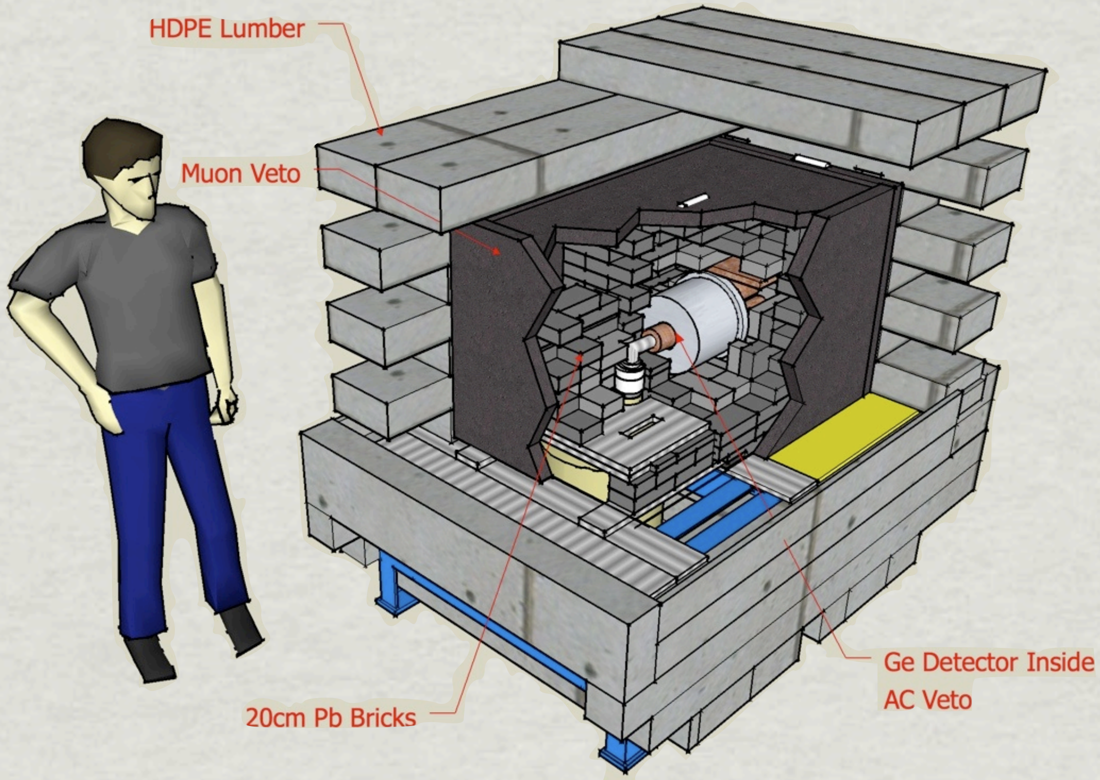
P. S. Barbeau, J. I. Collar, and O. Tench., JCAP, 2007(09):009, 2007.

CoGeNT: SONGS deployment

- Deployed the CoGeNT detector to the San Onofre Nuclear Generating Station (SONGS)
- Tendon Gallery (30 m.w.e.) modest protection from atmospheric cosmic-ray backgrounds

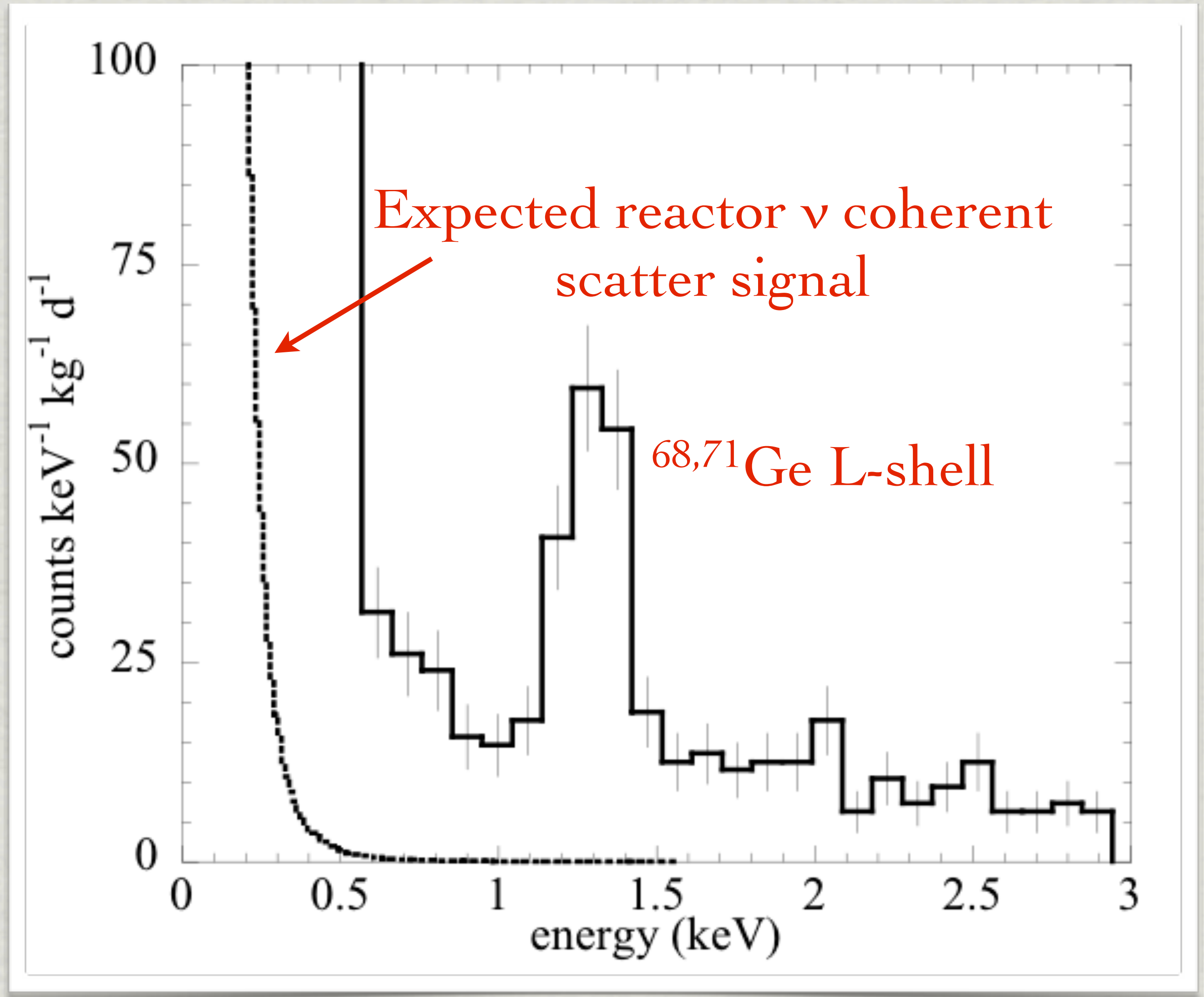






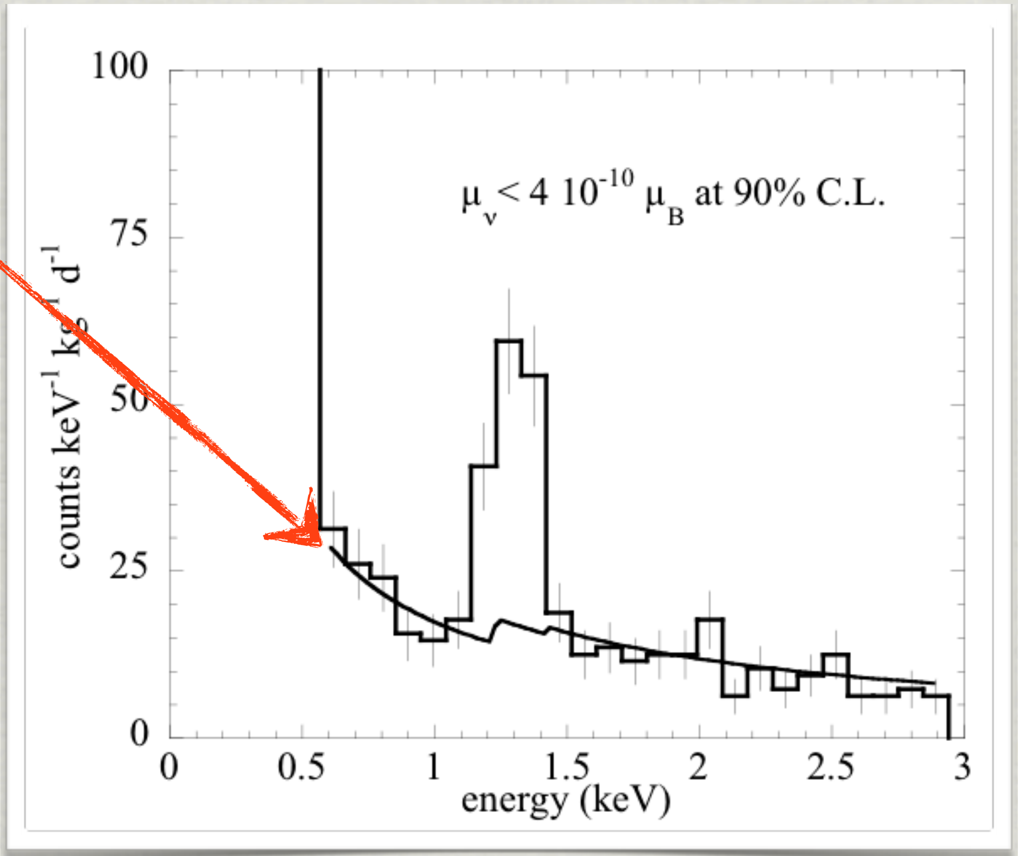
CoGeNT: SONGS results

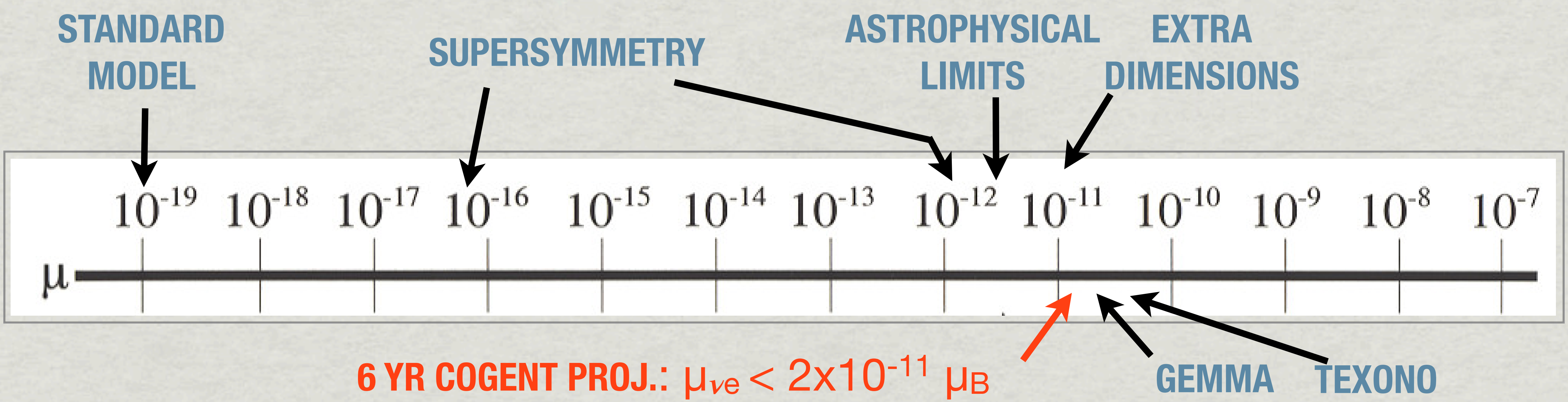
- After waiting significant cool-down period due to cosmogenic activation (from $^{68,71}Ge$), still dominated by backgrounds
- → Head deeper to the Soudan Underground Laboratory
- Lower threshold would be nice



Bonus: ν-e scattering μ_ν search

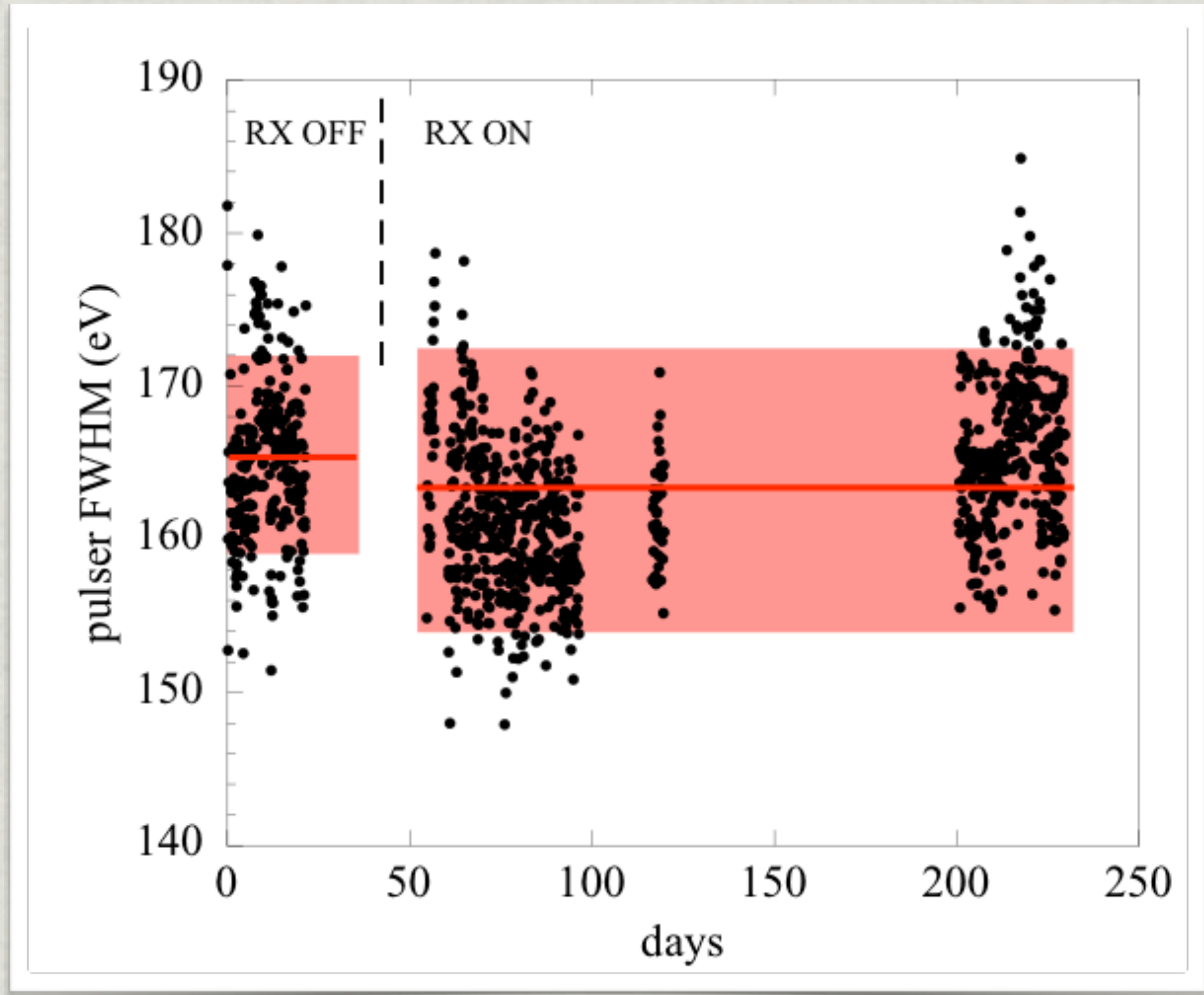
- Search for characteristic 1/T spectrum
- Unable to subtract Rx-off background due to cosmogenic activation & Rx shutdown → this limit not competitive (GEMMA: $\mu_{\nu e} < 3.3\text{x}10^{-11}$ μ_B)





Bonus: ν dE/dx

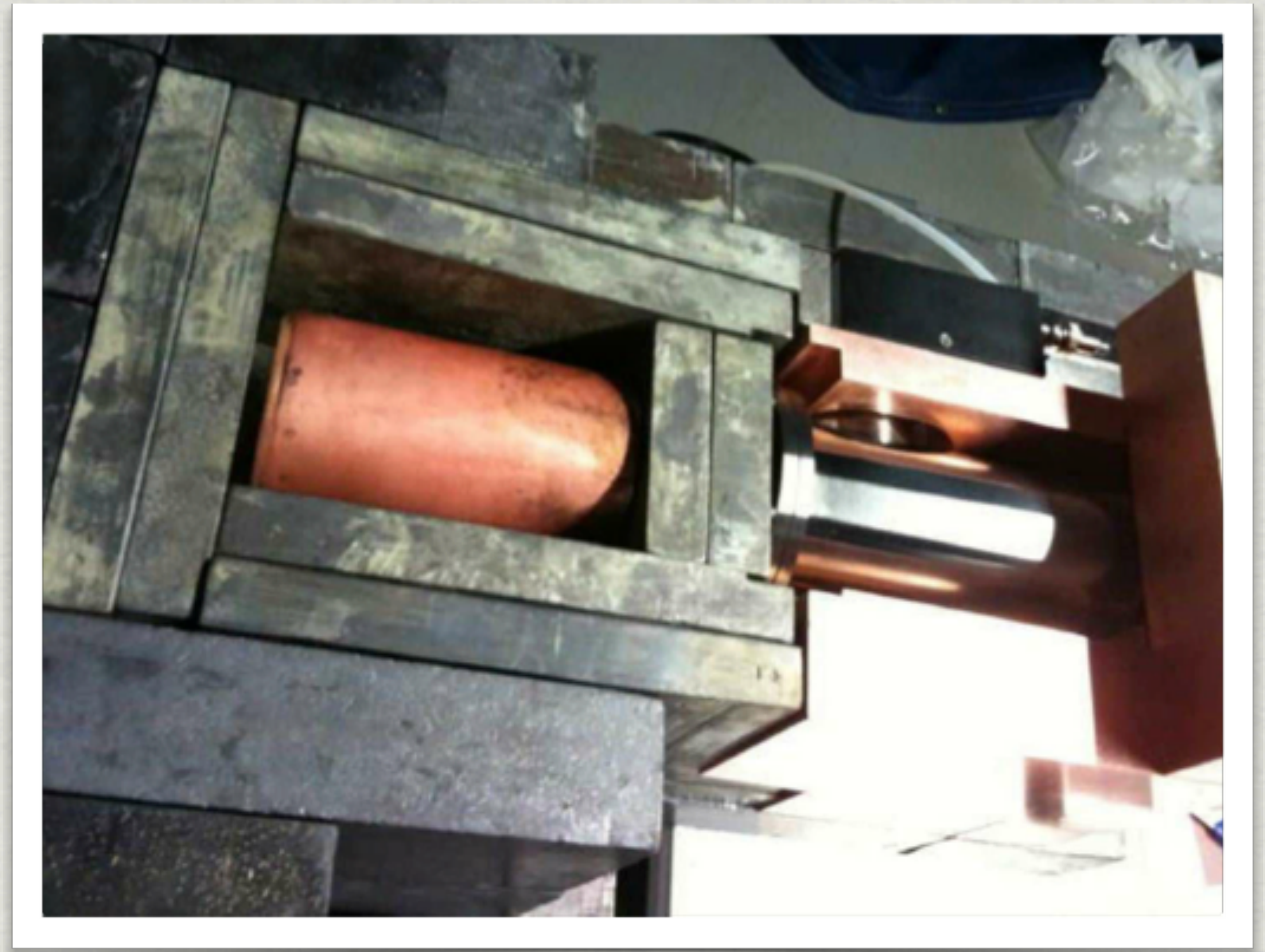
- By monitoring leakage current, we can constrain the ν dE/dx from large flux of Rx neutrinos ($\sim 10^{13}$ ν's cm^{-1} s^{-1})
- $dE/dx < 4.6 \times 10^{-8}$ eV cm^{-1}
- ~ 200 improvement over previous result (at one time, this was a possible explanation of the solar neutrino problem)



F. Vanucci , Nucl Phys. B 70 (1999) 199-200; A. Castera *et al., Phys. Lett. B 452 (1999) 150-154*

CoGeNT Background Characterization: Soudan

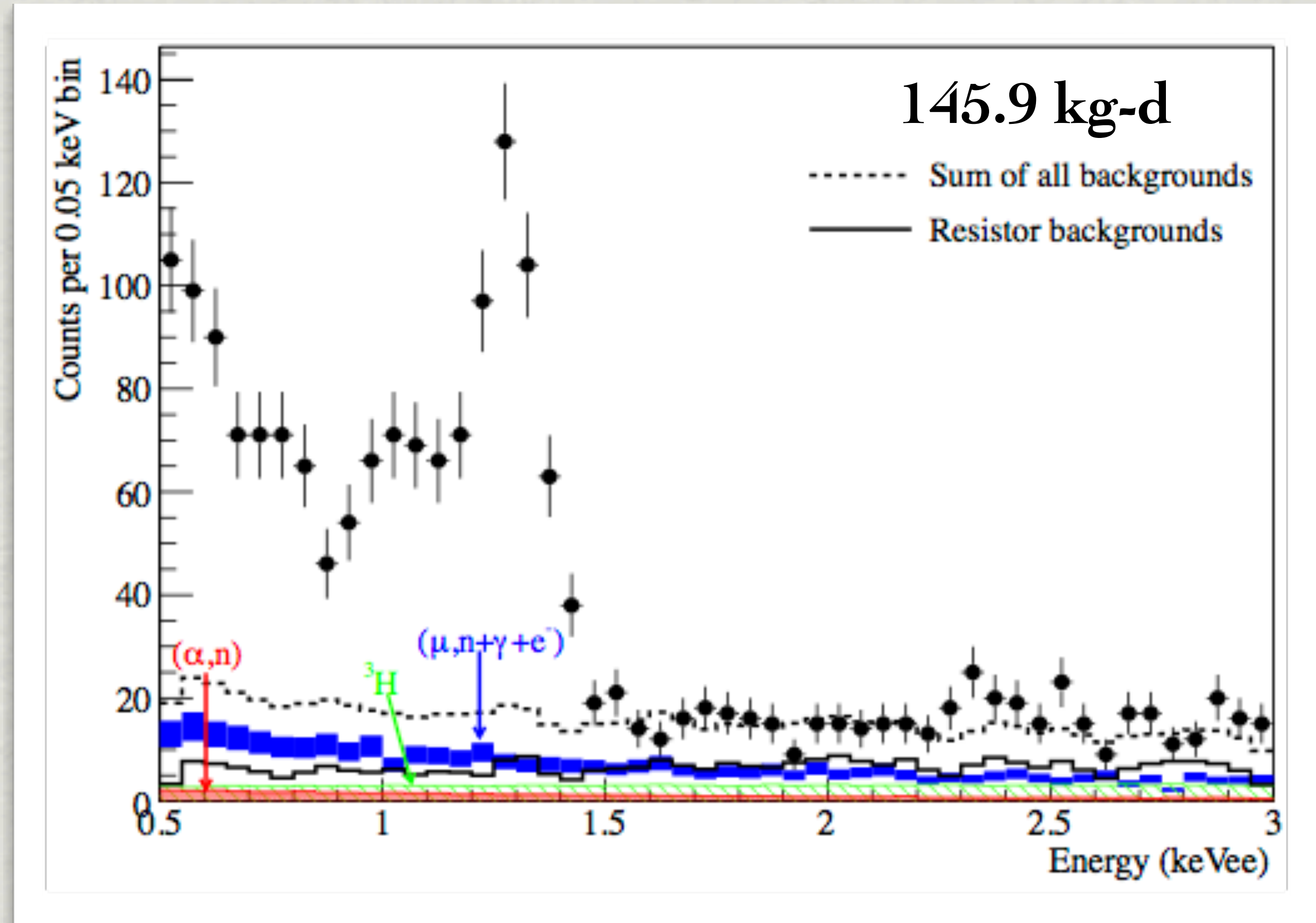
- Re-deployed the detector with modified shielding to the Soudan underground laboratory (Autumn 2009)



C. Aalseth, P. S. Barbeau, J. Colarisi, et al., arXiv:1208.5737

CoGeNT Background Characterization: Soudan

- Dominant backgrounds from gamma emitters in construction material
- While there, performing searches for light WIMPs and axion-like Dark Matter



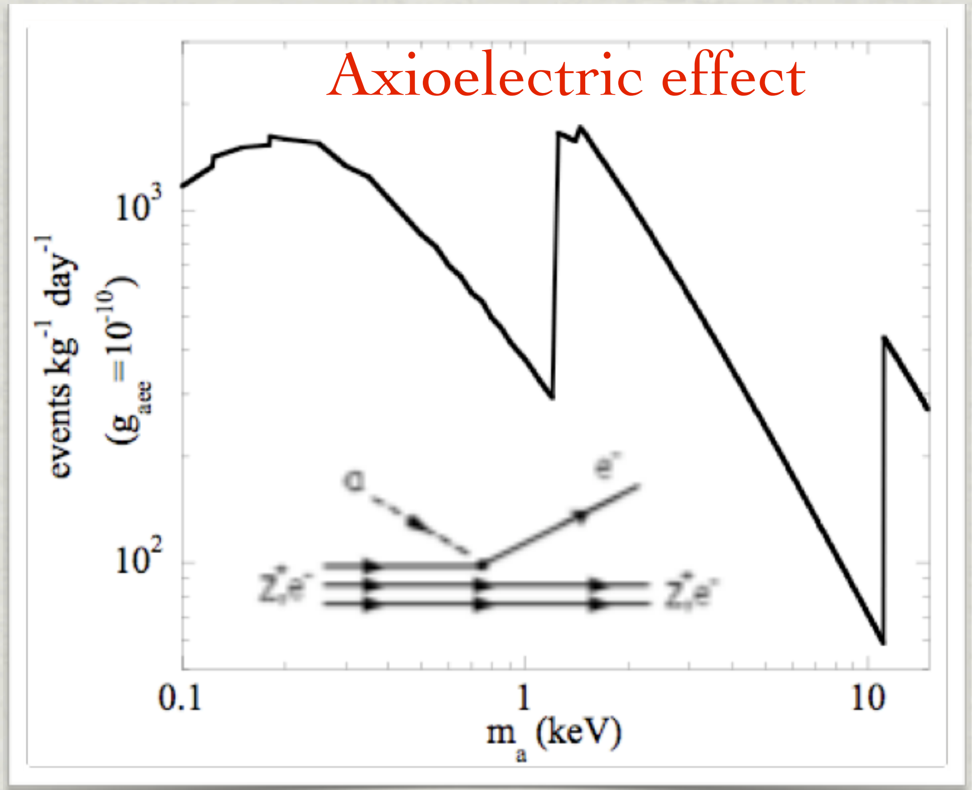
C. Aalseth, P. S. Barbeau, J. Colarisi, et al., arXiv:1208.5737

...for Dark Matter searches

- 20-30% of the mass-energy of the universe is likely made up of non-relativistic, non-baryonic Dark Matter
- Mounting evidence: Coma Cluster, Galactic rotation curves, gravitational lensing, bullet cluster, CMB measurements, BBN...
- search for non ad-hoc candidates interacting in detectors: axions, neutralinos, sterile neutrinos...

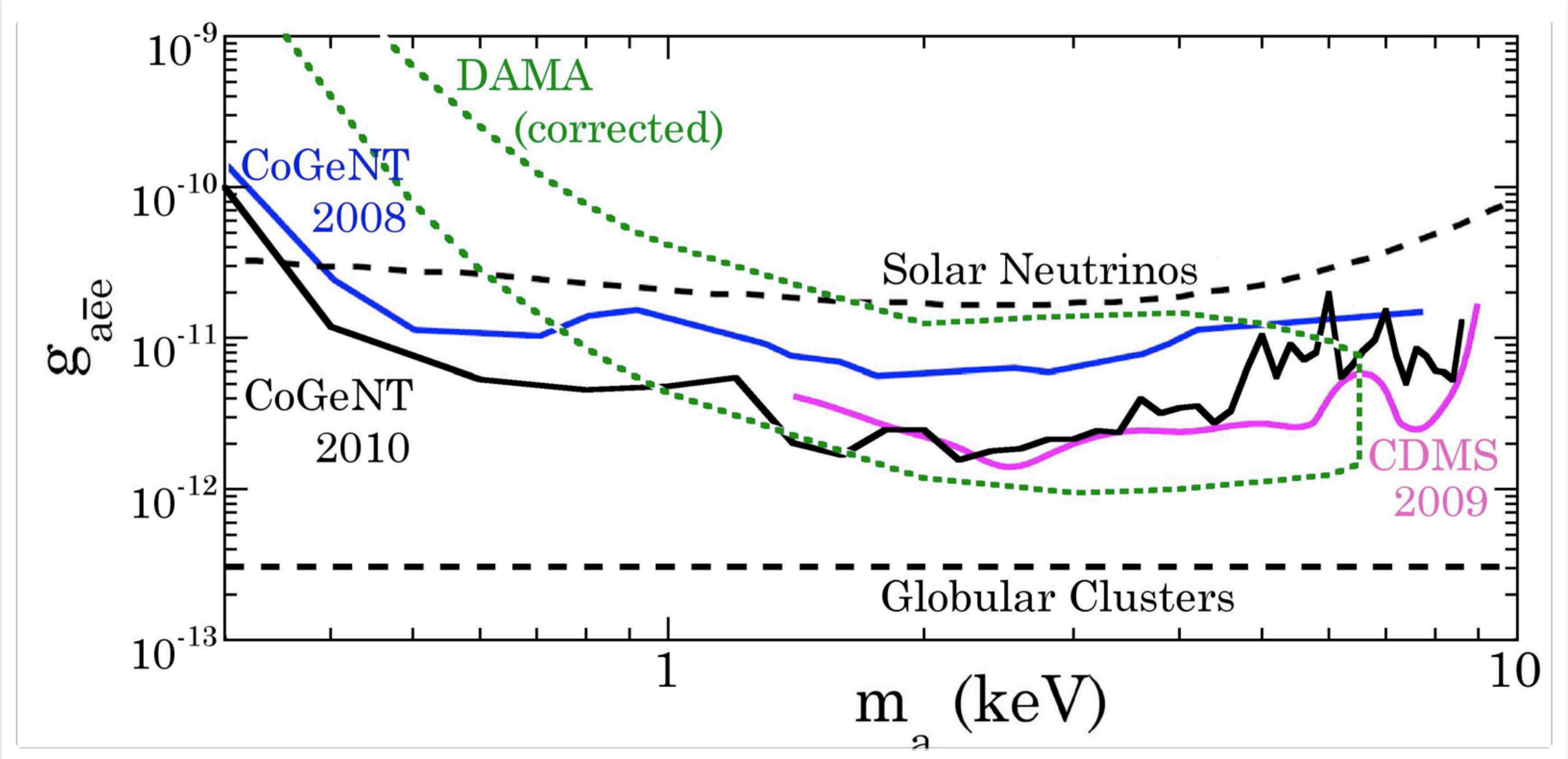
BULLET CLUSTER

Axion search at Soudan



- Axion: hypothetical particle that arises from solutions to the strong CP problem.

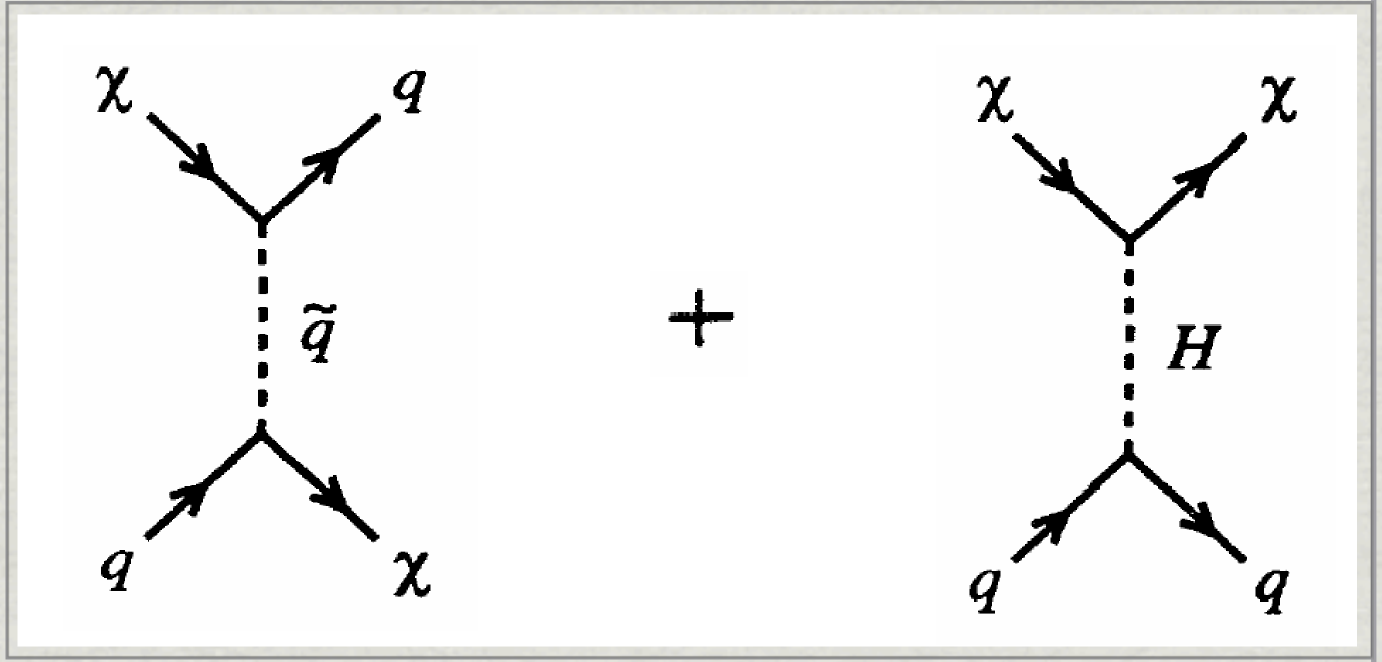
- Search for unexpected peaks due to the axioelectric effect



C. Aalseth, P. S. Barbeau, N. S. Bowden, et al., Phys. Rev. Lett. 106 (2011) 131301

...WIMPs

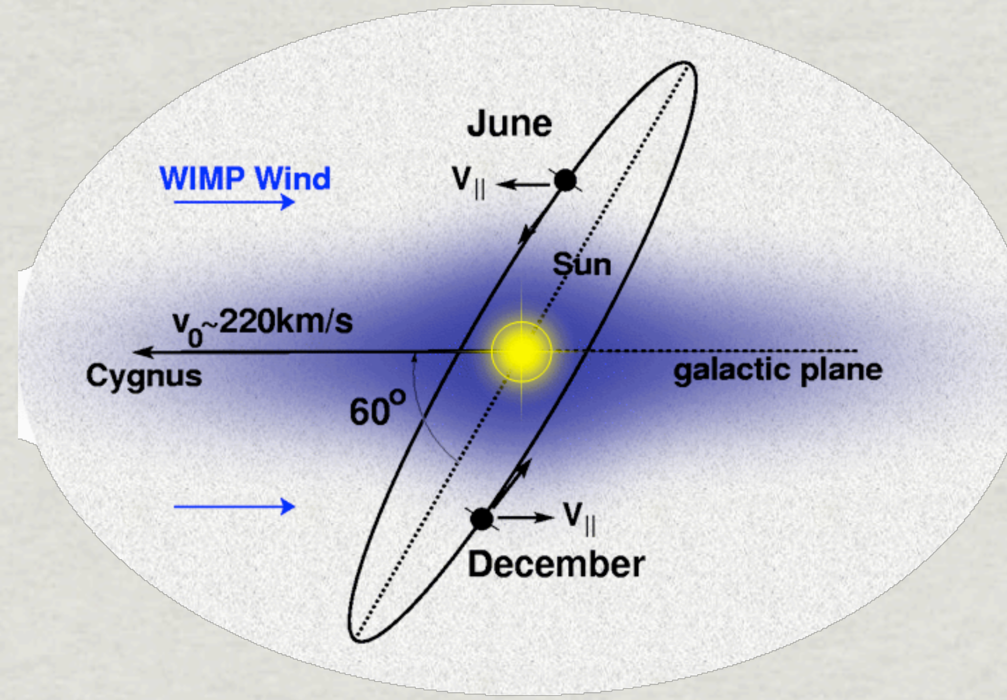
- WIMPS, neutralinos, etc., arise in Supersymmetric theories
- Weakly Interacting Massive Particles can undergo **coherent nuclear elastic scattering**
- → low energy nuclear recoils
- $\sigma \propto A^2$

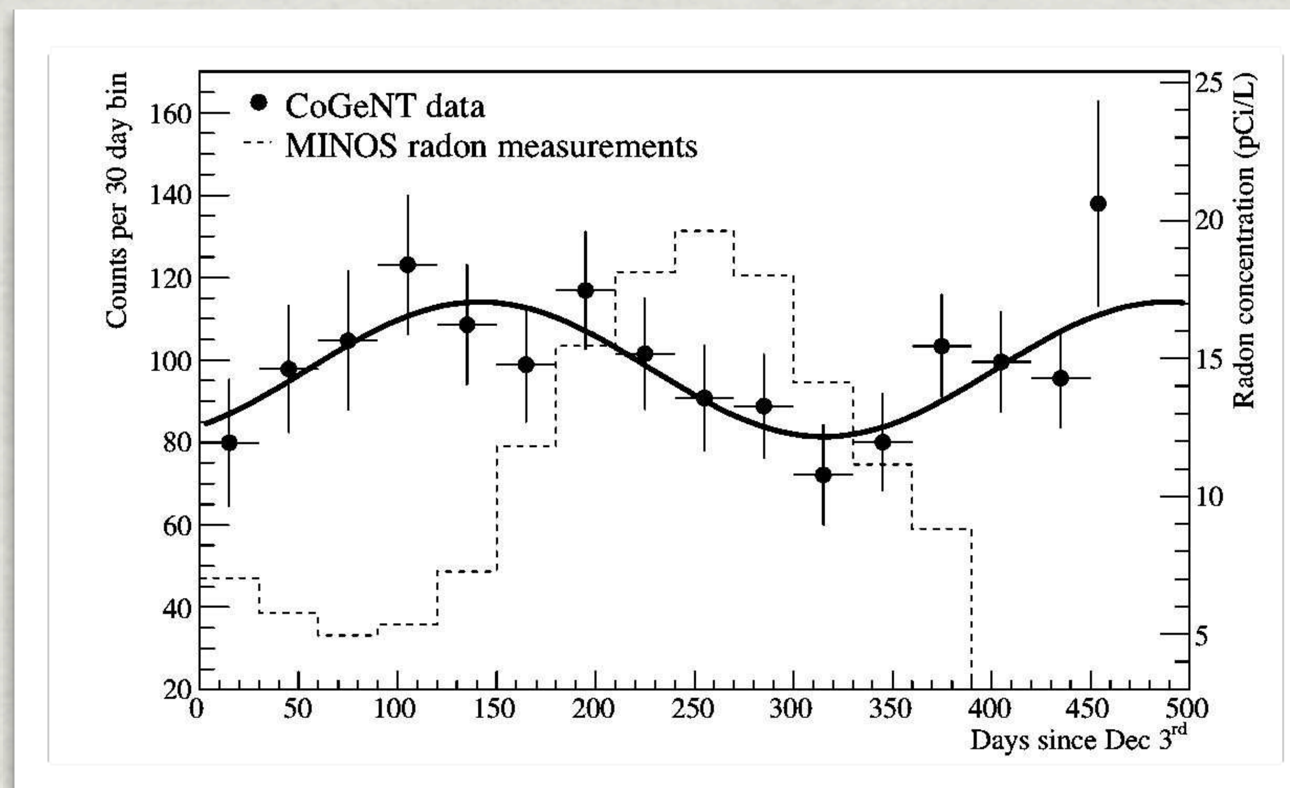


Spin-Independent neutralino-quark coupling

WIMP search at Soudan

- CoGeNT saw a hint of an annual modulation for “Light WIMPs”.
  (in 0.5-3.0 keV region)
- annual modulation of interaction rate key signature of galactic dark matter
- inconsistent with known sources of modulating backgrounds (muons, Rn)
- CoGeNT recently passed 3 year mark (Dec 2012)



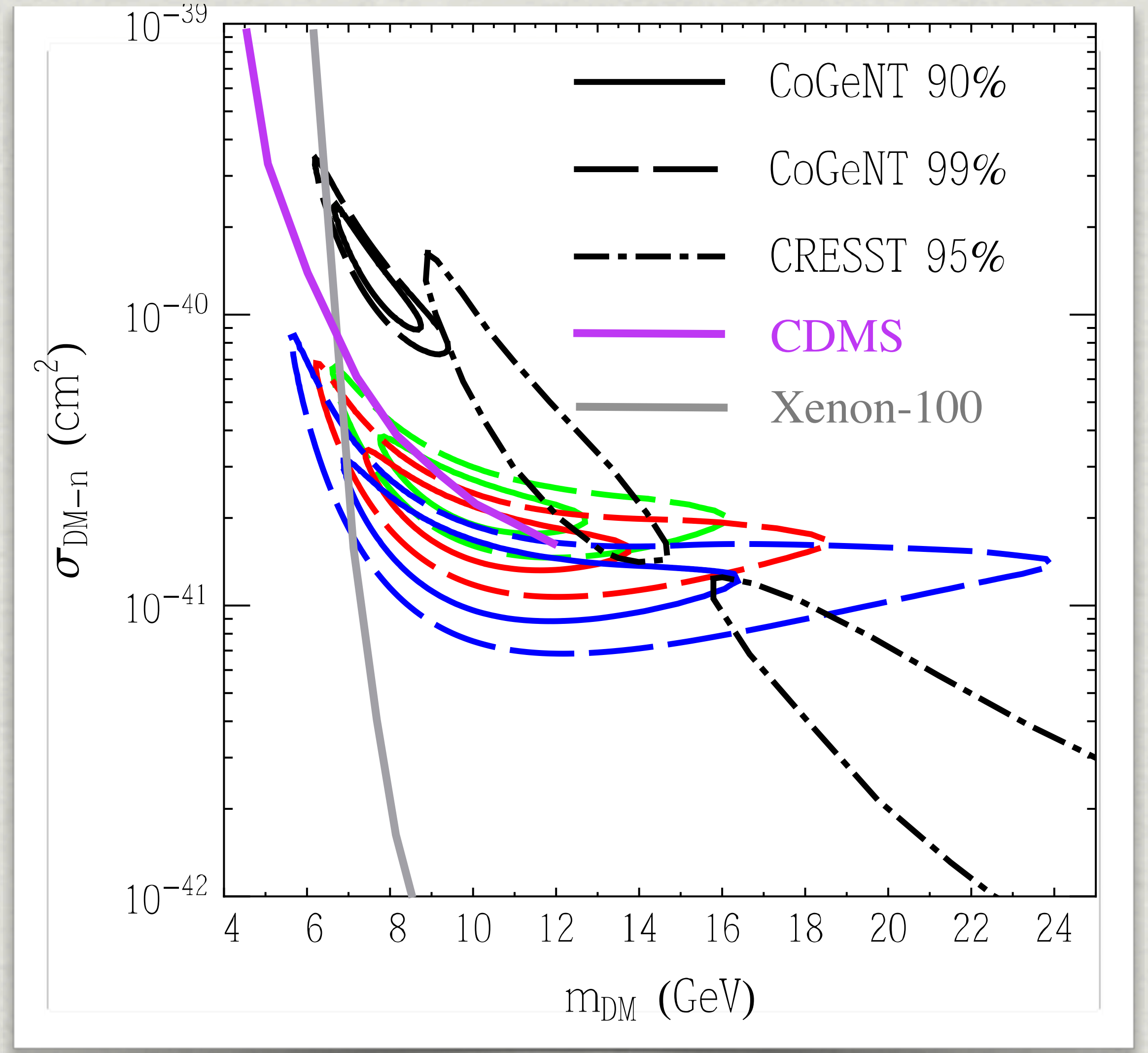


C. Aalseth, P. S. Barbeau, J. Colarisi, et al., Phys. Rev. Lett. 107 (2011) 141301

C. Aalseth, P. S. Barbeau, J. Colarisi, et al., arXiv: 1208.5737

Similarities & Inconsistencies

- Possible to reconcile this putative signal with others (e.g. CRESST/DAMA): *Large M_{DM} uncertainty*
- However: this light WIMP favored region appears to be contradicted by exclusion limits from Xenon-100: *Possible Isospin violating Dark Matter, Form Factor uncertainty?*
- Modulation signal not seen in CDMS(Ge): *Threshold uncertainties (QFs)? Electron interacting DM? Streams?*
- Modulation magnitude significantly larger than vanilla models: *non-Maxwellian DM velocity halo? (non-thermal streams)*



C. Kelso, D. Hooper, M.R. Buckley, Phys. Rev. D 85 043515 (2012)

CDMS & CoGeNT

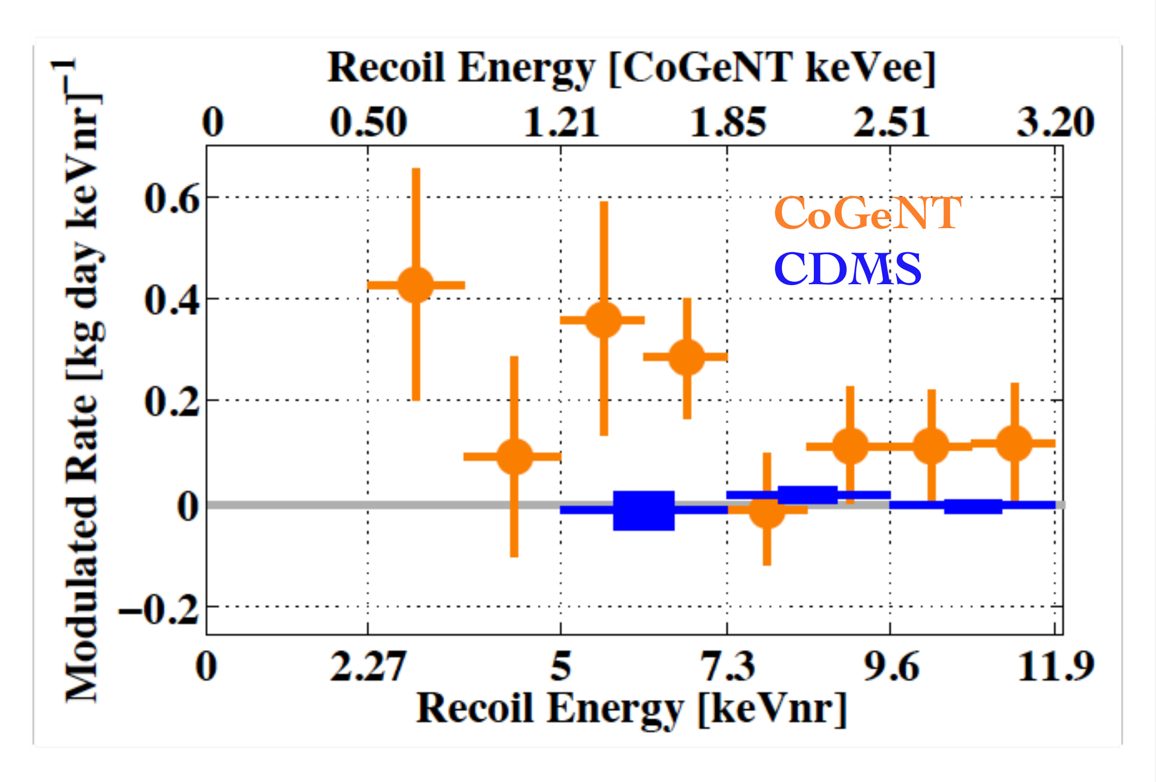
* Important: same isotope and location
* The thresholds for nuclear recoils differ
* Uncertainty in threshold from QF (10%)
* Tidal Streams can complicate the expected modulation amplitude & phase
* CDMS data does not constrain the possibility of electron-interacting DM (Dark Pseudoscalars, Luminous DM, etc.)

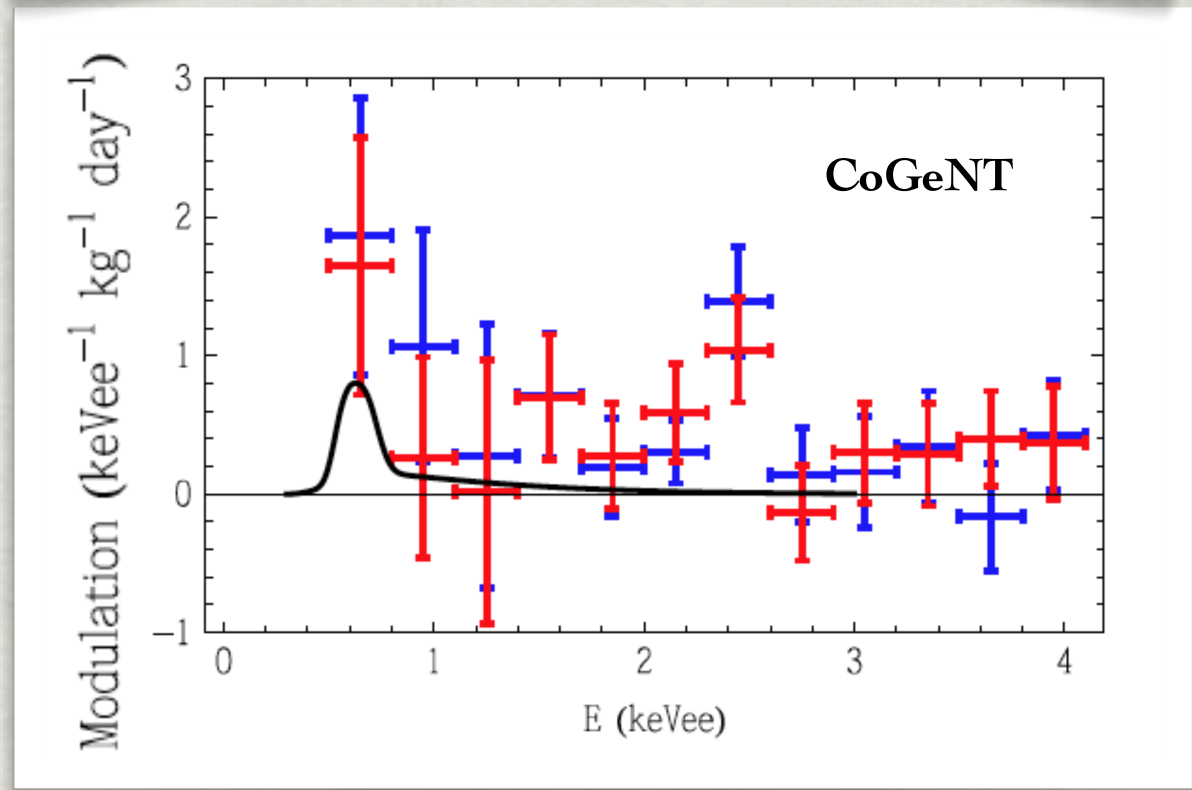
P. W. Graham, R. Harnik, S. Rajendran, P. Saraswat, Phys.Rev.D82:063512,2010

* Or more exotic models: Exothermic DM

B. Feldstein, P. W. Graham, P. Saraswat, Phys.Rev.D82:075019,2010

CDMS II arXiv:1203.1309





C. Kelso, D. Hooper, M.R. Buckley, Phys. Rev. D 85 043515 (2012)

Solution: MAGν_eT (for lack of a better name)

- We are left with a detector that is nearly capable of observing coherent neutrino scattering, and a confusing picture of light WIMP hints & exclusions

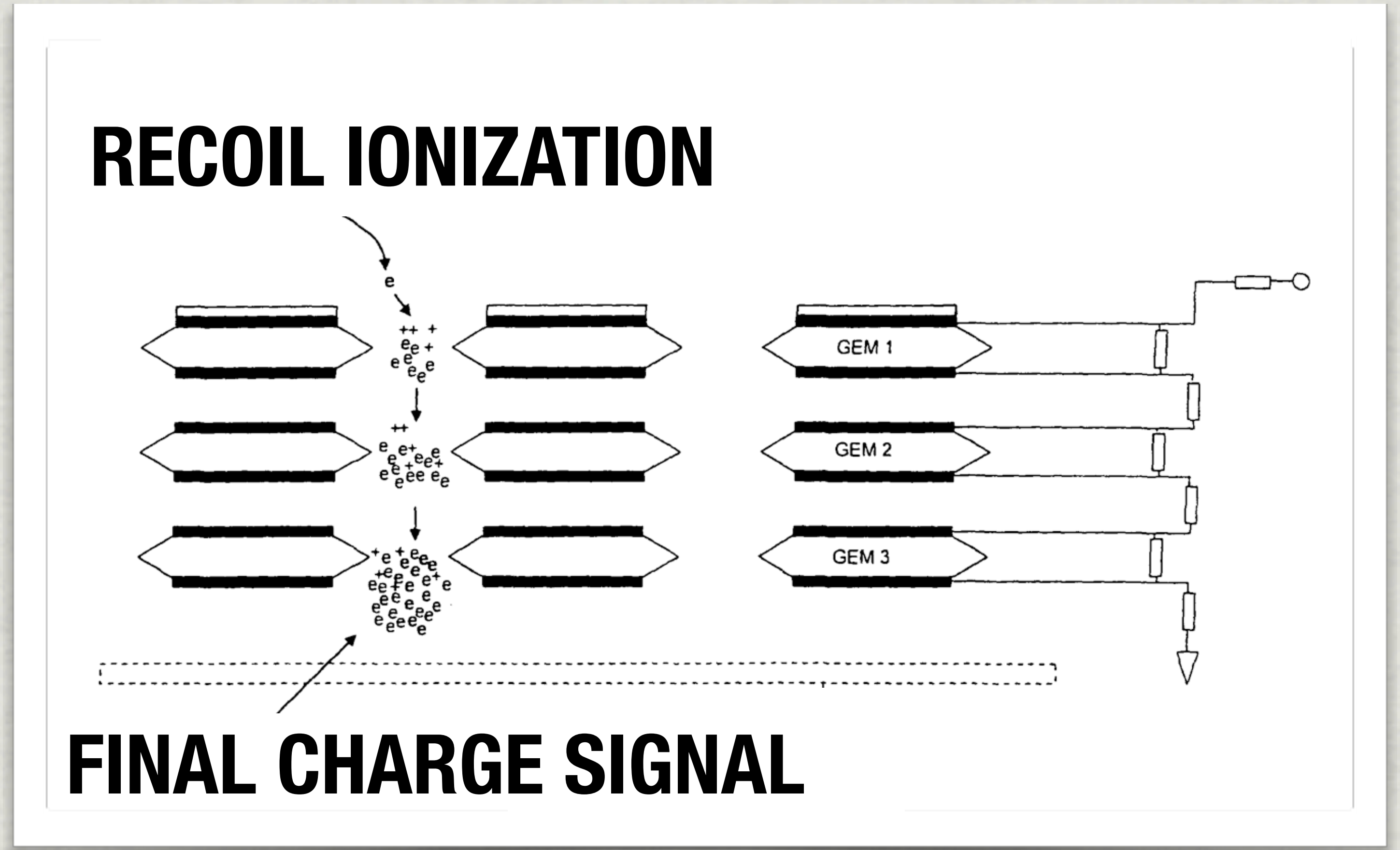
- MAGν_eT addresses detector systematics, backgrounds, theoretical particle physics, astroparticle physics & measurement uncertainties with a simple common detector construction capable of using dozens of target nuclei

- Return to an old effort from the pre-history of CoGeNT: low threshold kg-scale gas detectors (GEMs, etc.)

P. S. Barbeau, J. I. Collar, IEEE Trans.Nucl.Sci. 50 (2003) 1285-1289

Low Threshold Gas Detectors

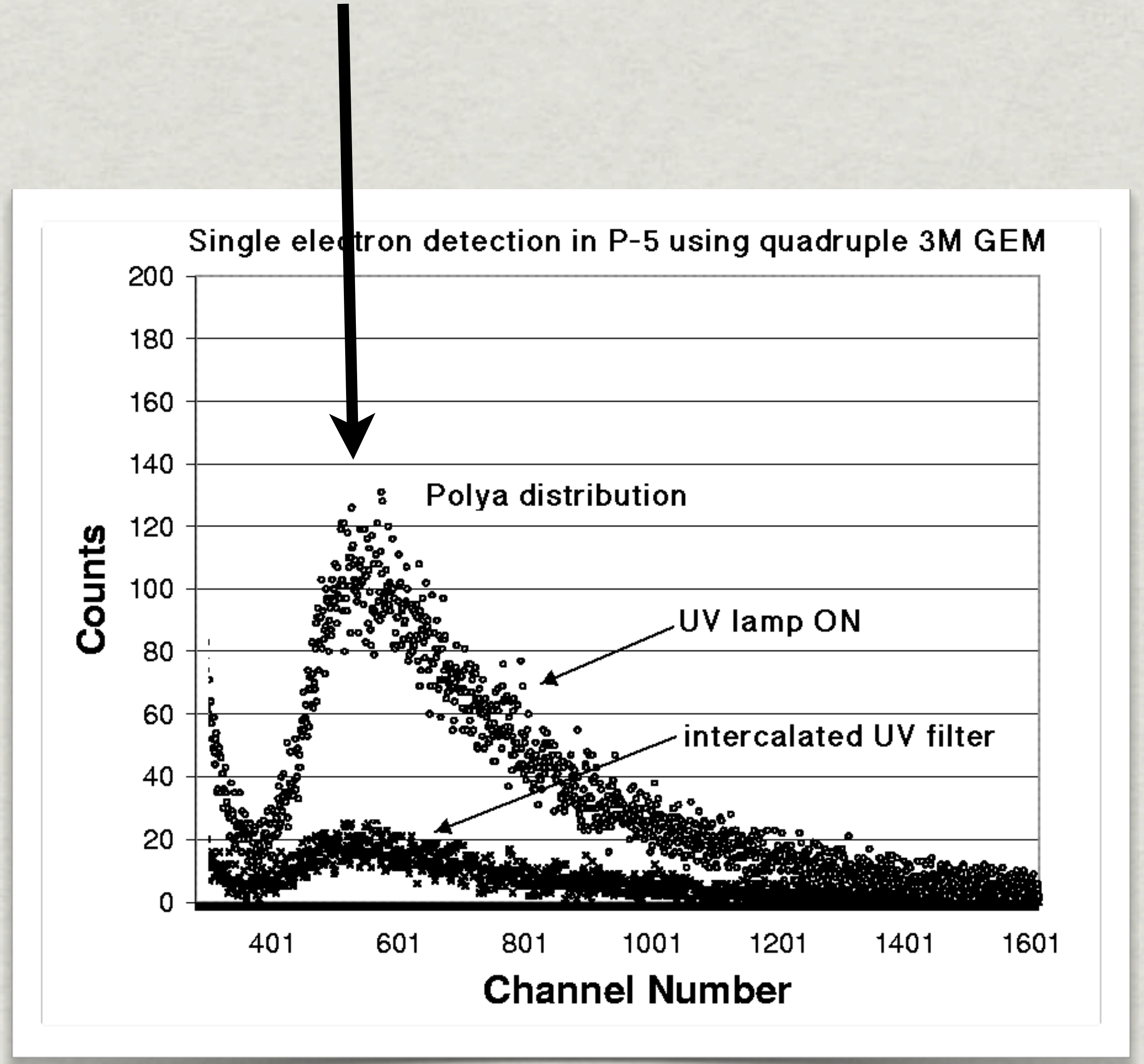
- Use low background, kg-scale gas detectors with proportional amplification (e.g. 3M GEMs)



P.S. Barbeau, J.I. Collar et al., NIM A515:439– 445, 2003.

Low Threshold Gas Detectors

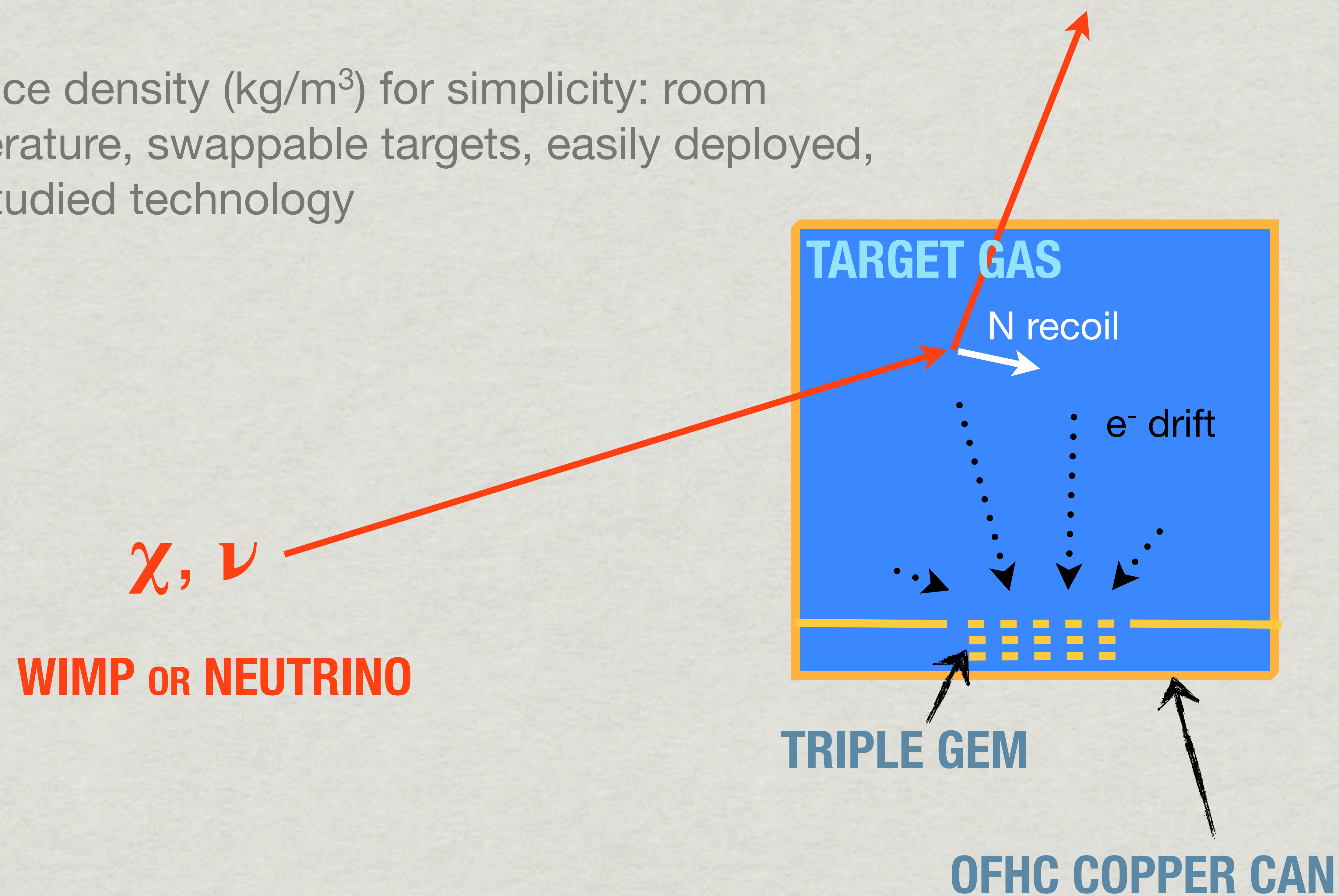
- Single electron sensitivity demonstrated (10's eV threshold)



P.S. Barbeau, J.I. Collar et al., NIM A515:439– 445, 2003.

Low Threshold Gas Detectors

- Sacrifice density (kg/m^3) for simplicity: room temperature, swappable targets, easily deployed, well studied technology



Target Gases

- Many swappable drift-gas targets
- With or without quench gases (CO_2, CH_4) or additives (TMAE, TEA)

H_2	$^{32,34}SF_6$
$^{3,4}He$	CO_2
$^{10,11}BF_3$	$^{20,22}Ne$
$^{12,13,14}CH_4$	N_2
C_2H_6	$^{82,83,84,85,86}Kr$
C_4H_{10} ...	$^{39,40}Ar$
CF_4	$^{129\text{-}132,134,136}Xe$

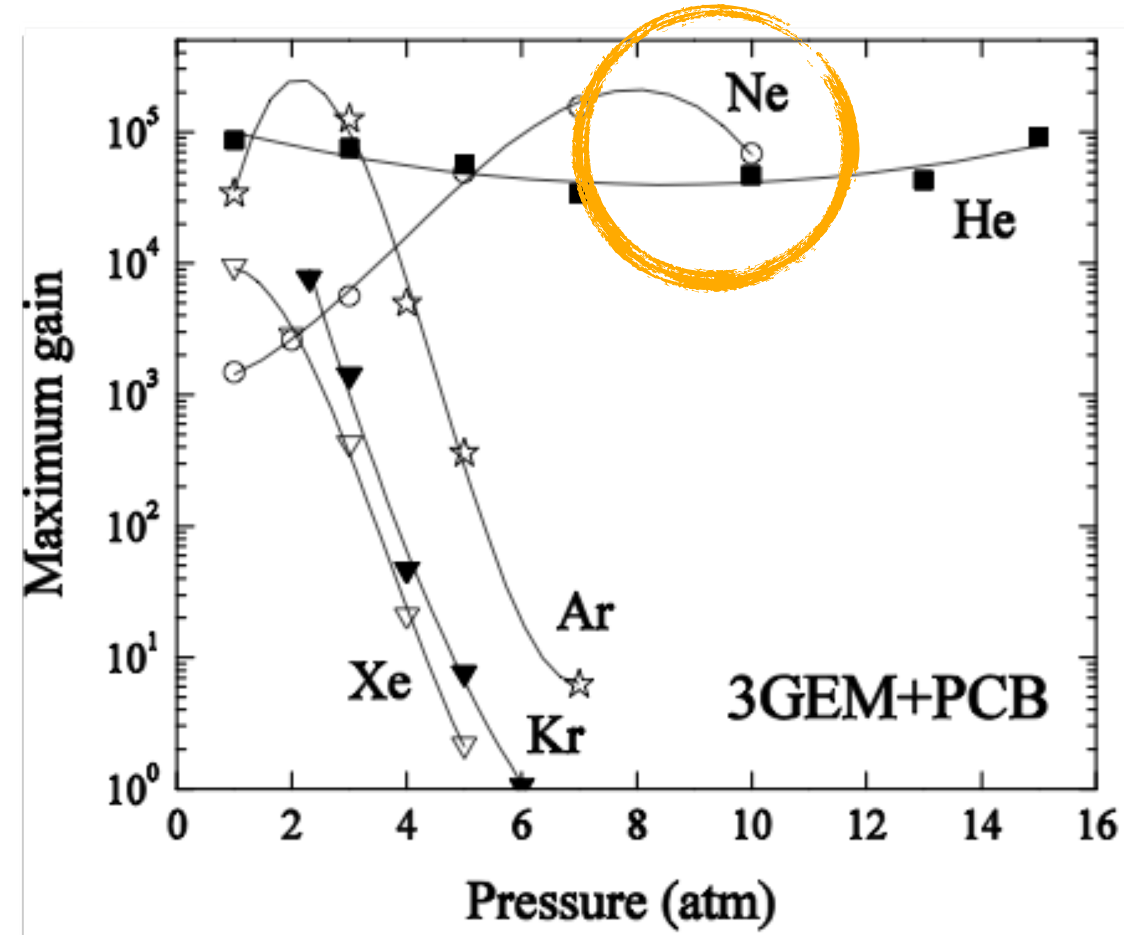
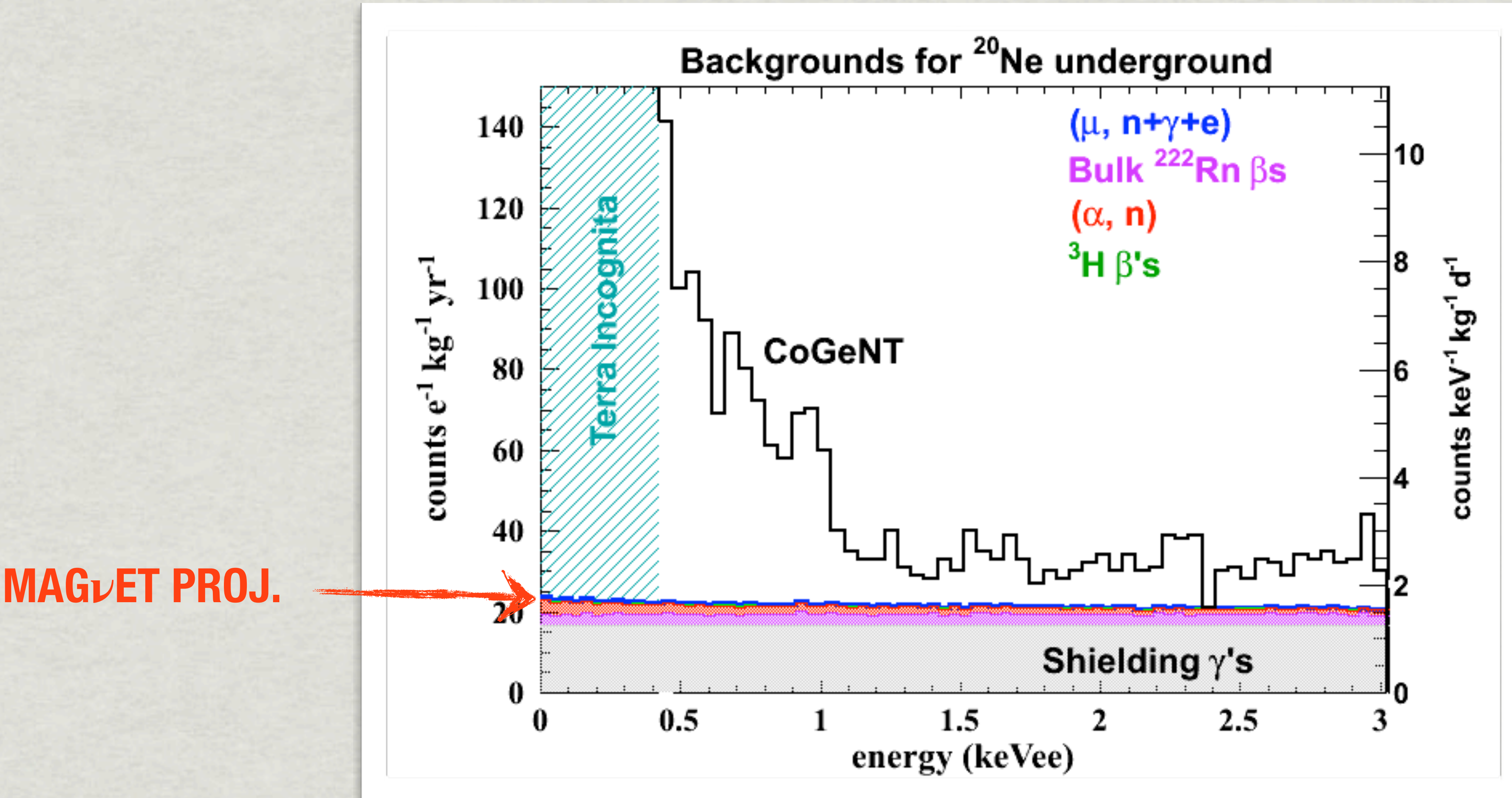


Fig.8 Maximum gain of a triple GEM detector as a function of pressure in He, Ne, Ar, Kr and Xe.

A. Buzulutskov et al, Nucl.Instrum.Meth. A493 (2002) 8-15

Low Backgrounds

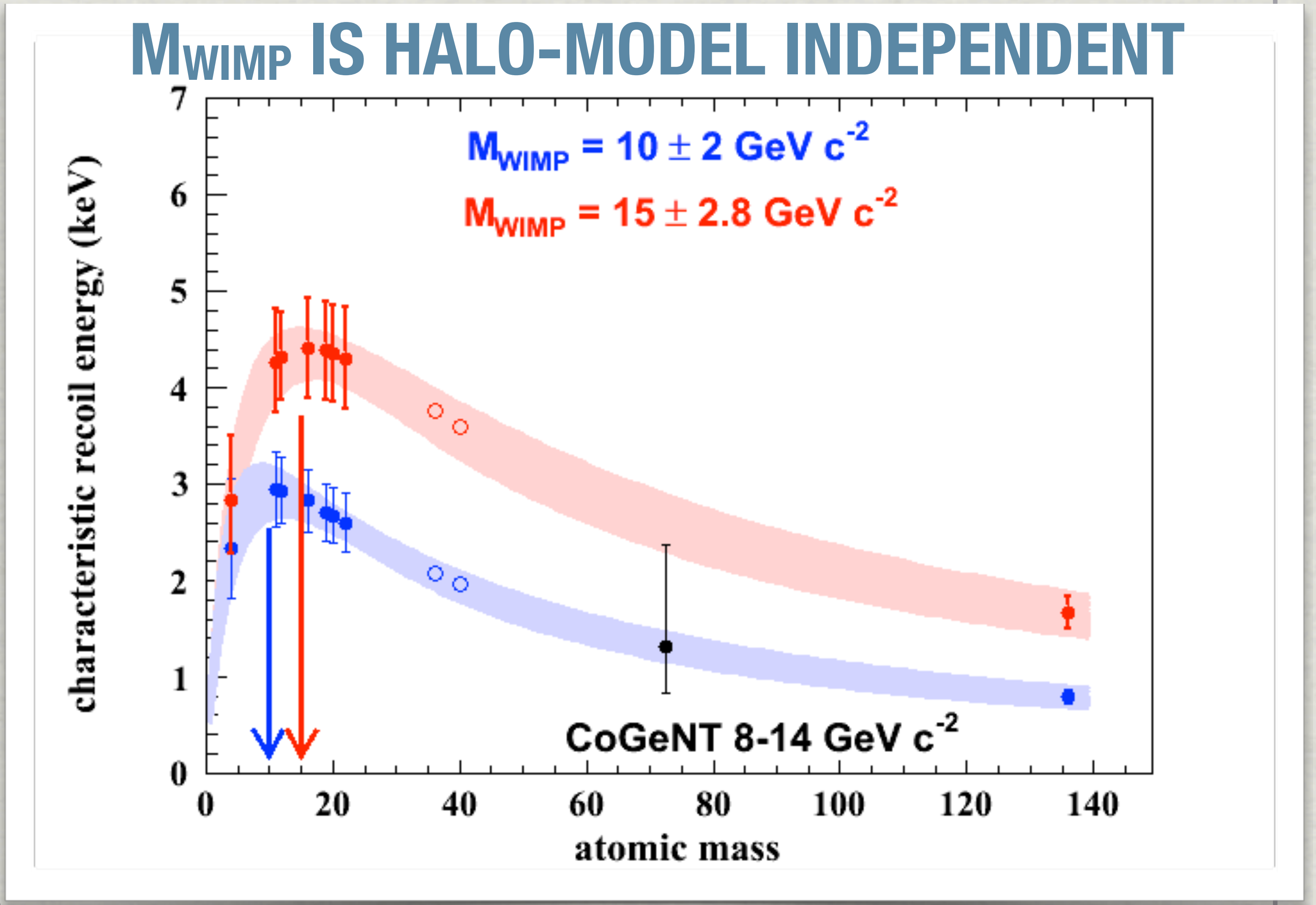


- Use what we can learn/extrapolate from CoGeNT to project backgrounds for ~ 20 eV threshold gas detectors
- Depending on the target gas, worry about ^{3}H, ^{14}C, ^{39}Ar, ^{85}Kr β's

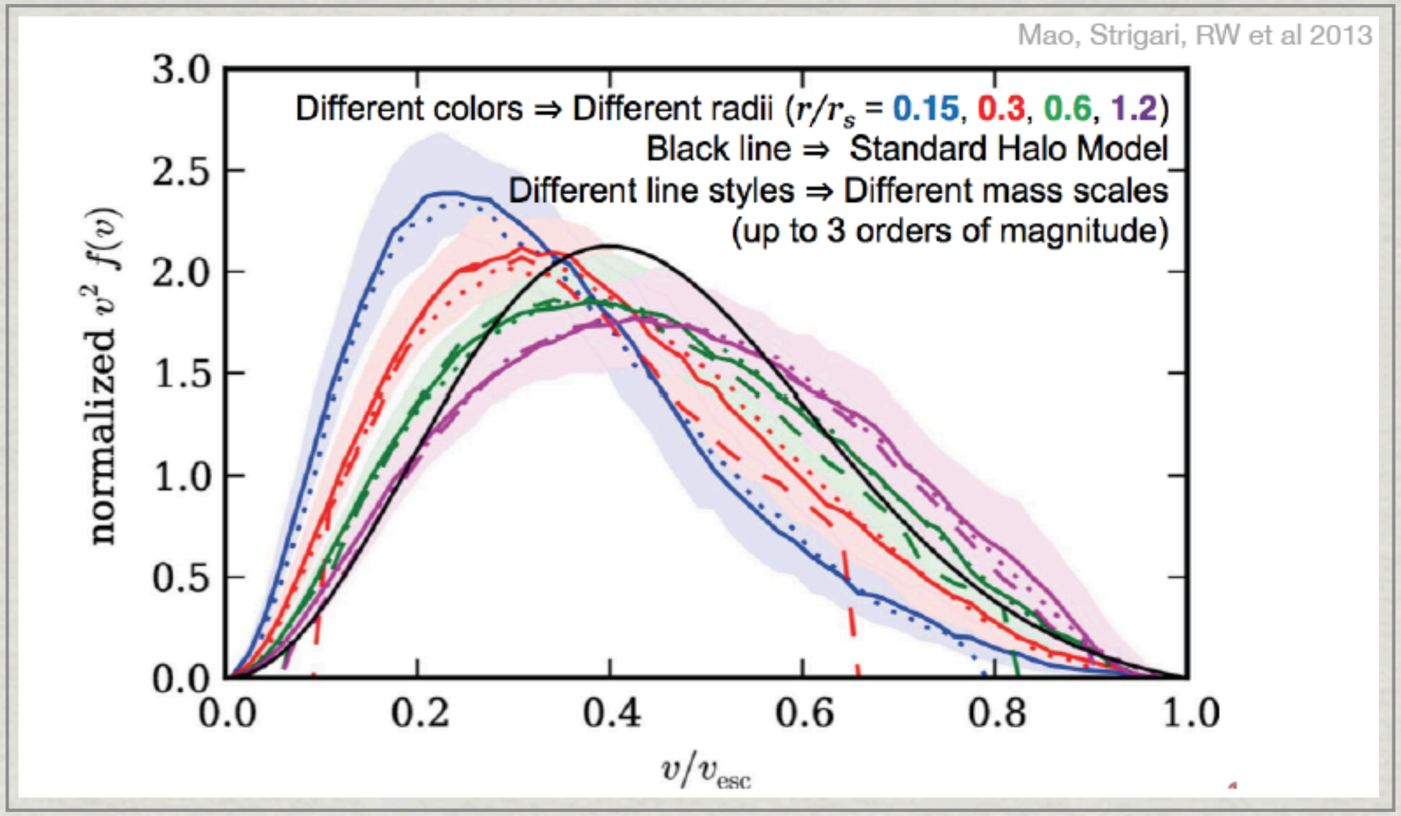
Light WIMP Search

- The kinematics of elastic WIMP-Nucleus scattering provides a precise determination of M_{DM} by studying the characteristic recoil energy of a signal versus atomic mass

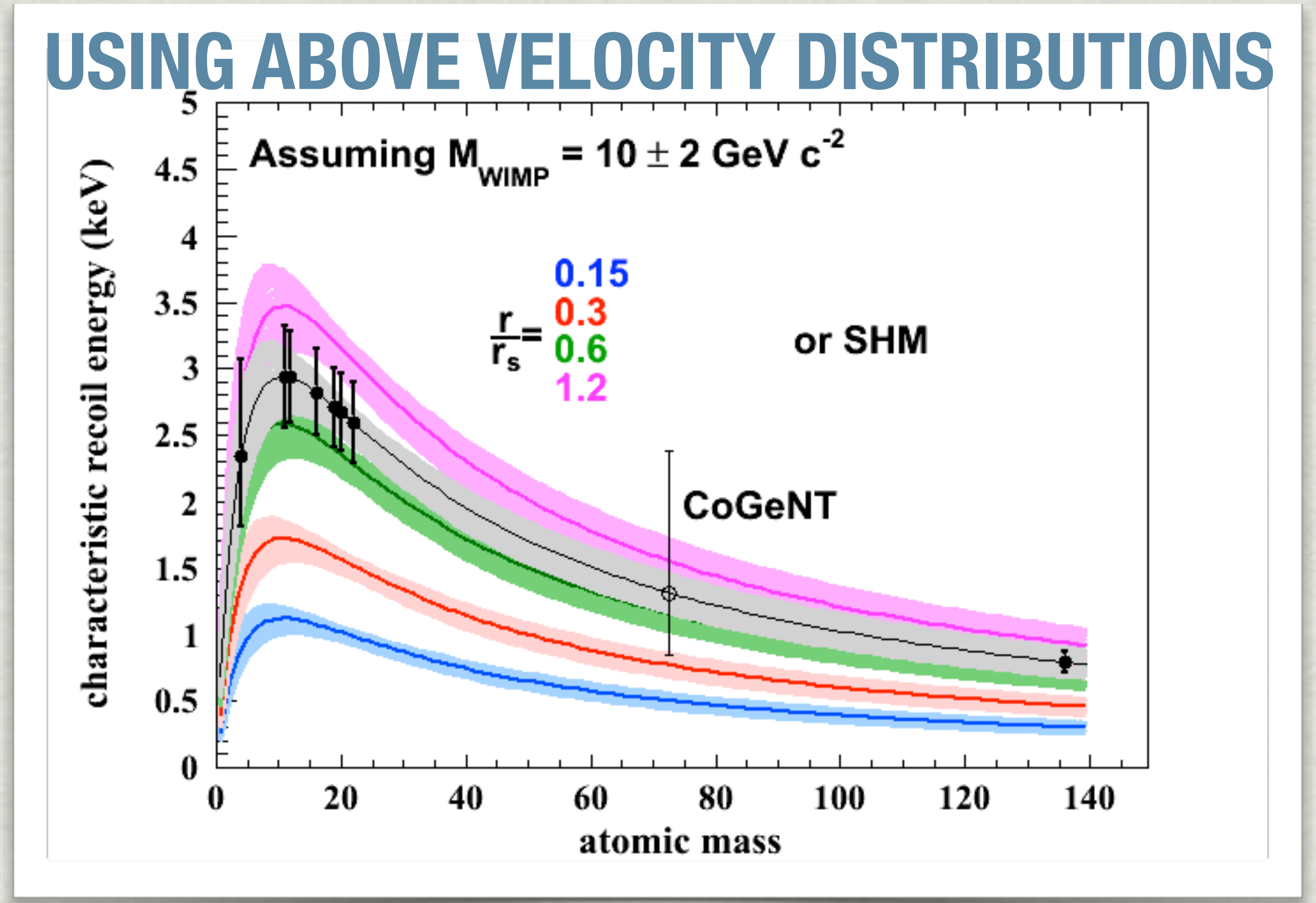
- This is also a check against possible neutron backgrounds



Cosmology: Non-Maxwellian Halo Models



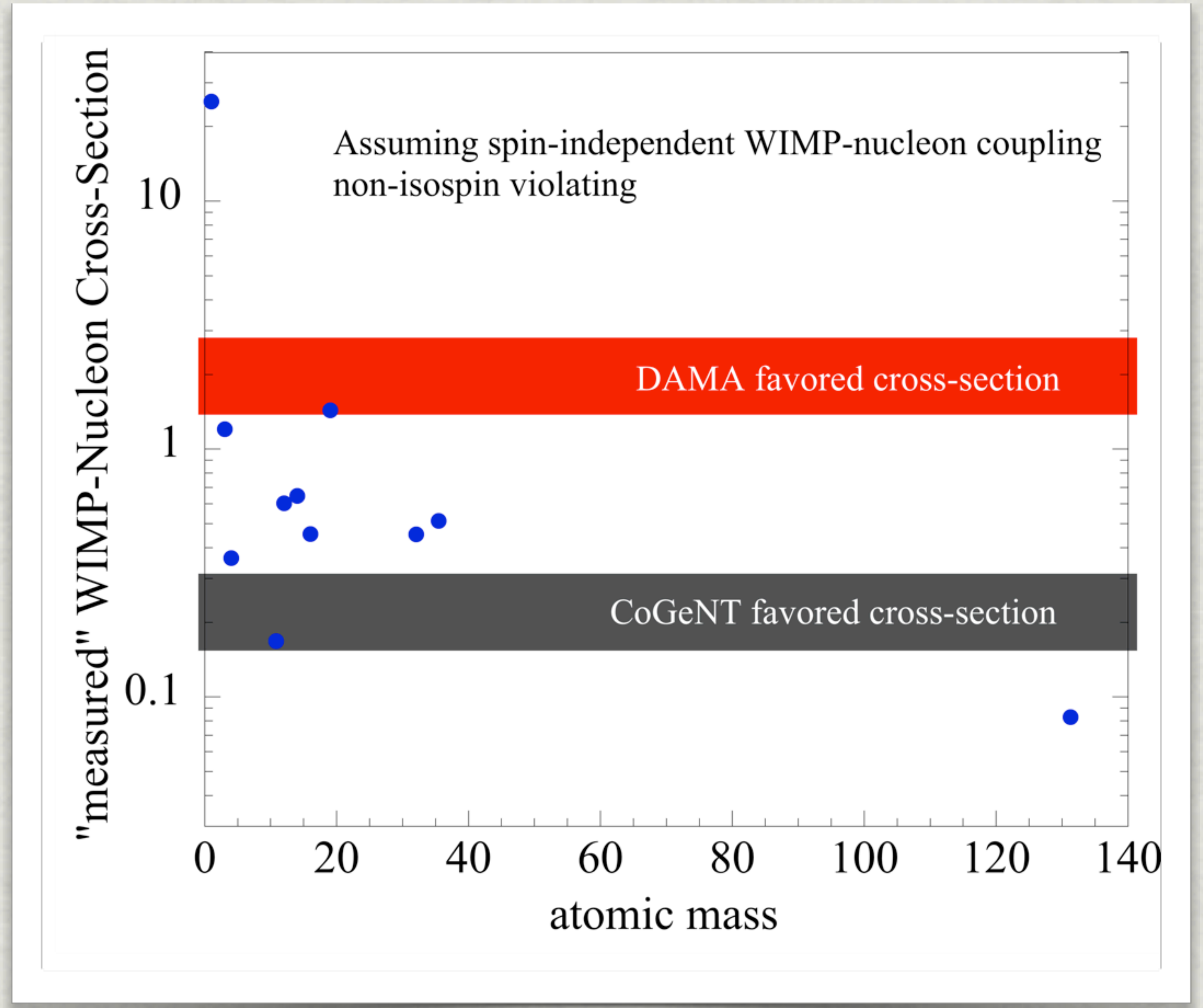
- Varying the target masses test different pieces of the velocity distribution function.



- Confirmed observation could potentially allow a systematic test of the Milky Way Dark Matter Halo

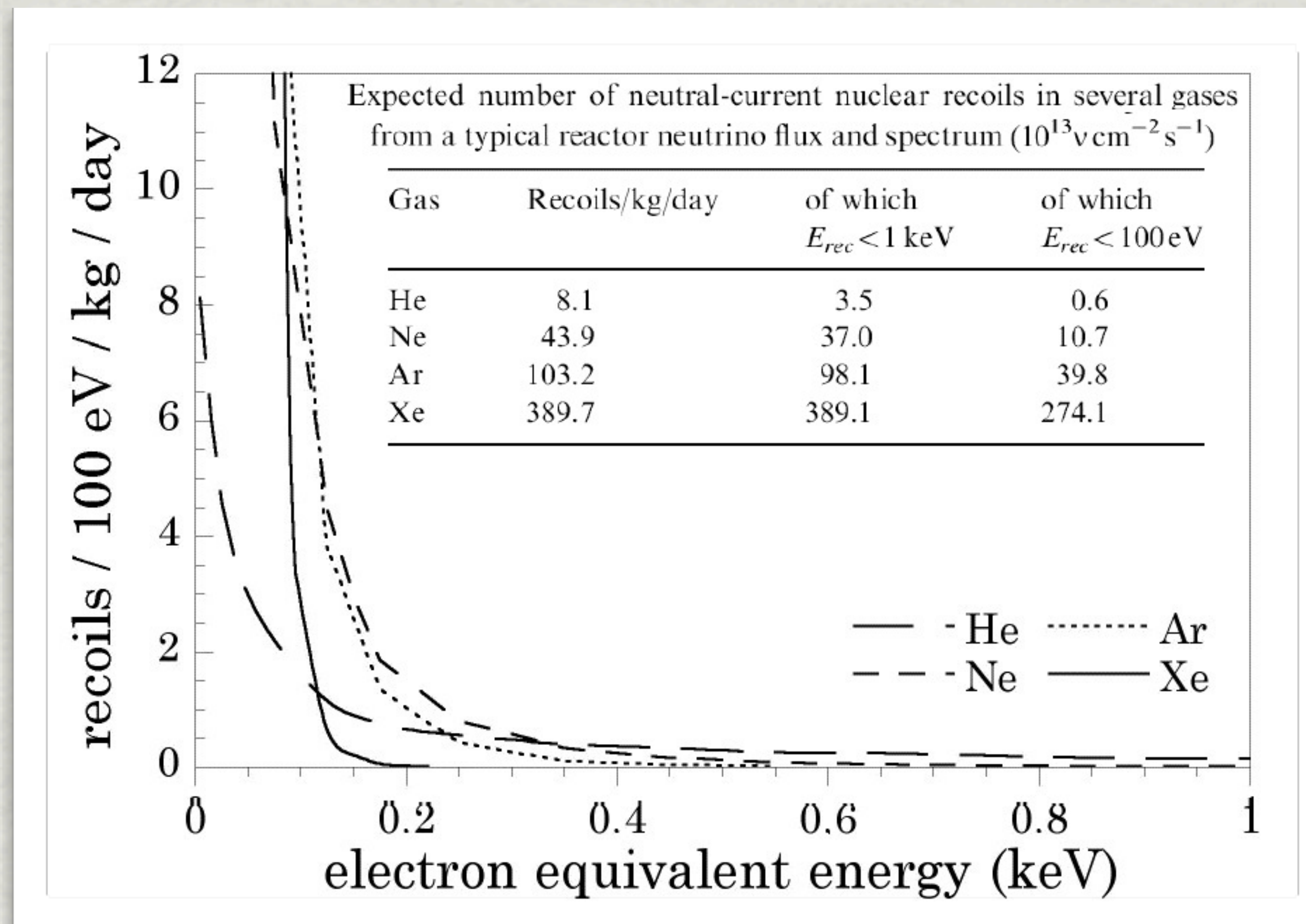
Light WIMP Search

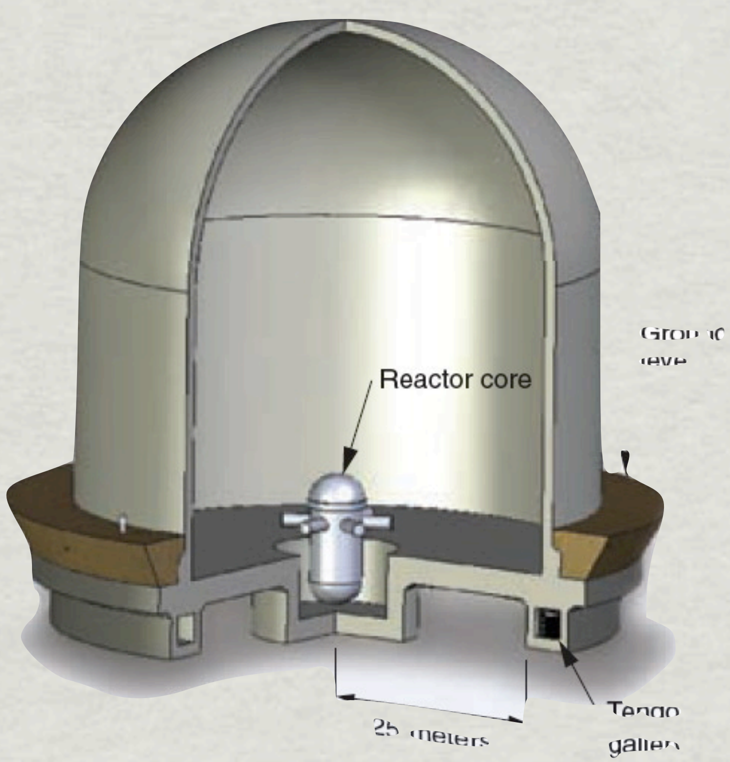
- Study the Coherent nature of the WIMP-Nucleus cross-section versus A
- Allows the identification of backgrounds with specific cross-section behaviors (neutrons, gammas, etc.)
- Constrain isospin-violating hypotheses, spin-dependent cross-sections → factorize out particle physics systematic



And While We Are at It: Coherent ν Scattering

- While backgrounds are being characterized in underground WIMP searches, we can also deploy detectors with several targets to **<u>reactors</u>** or <u>stopped pion beams</u> for coherent neutrino scattering experiments

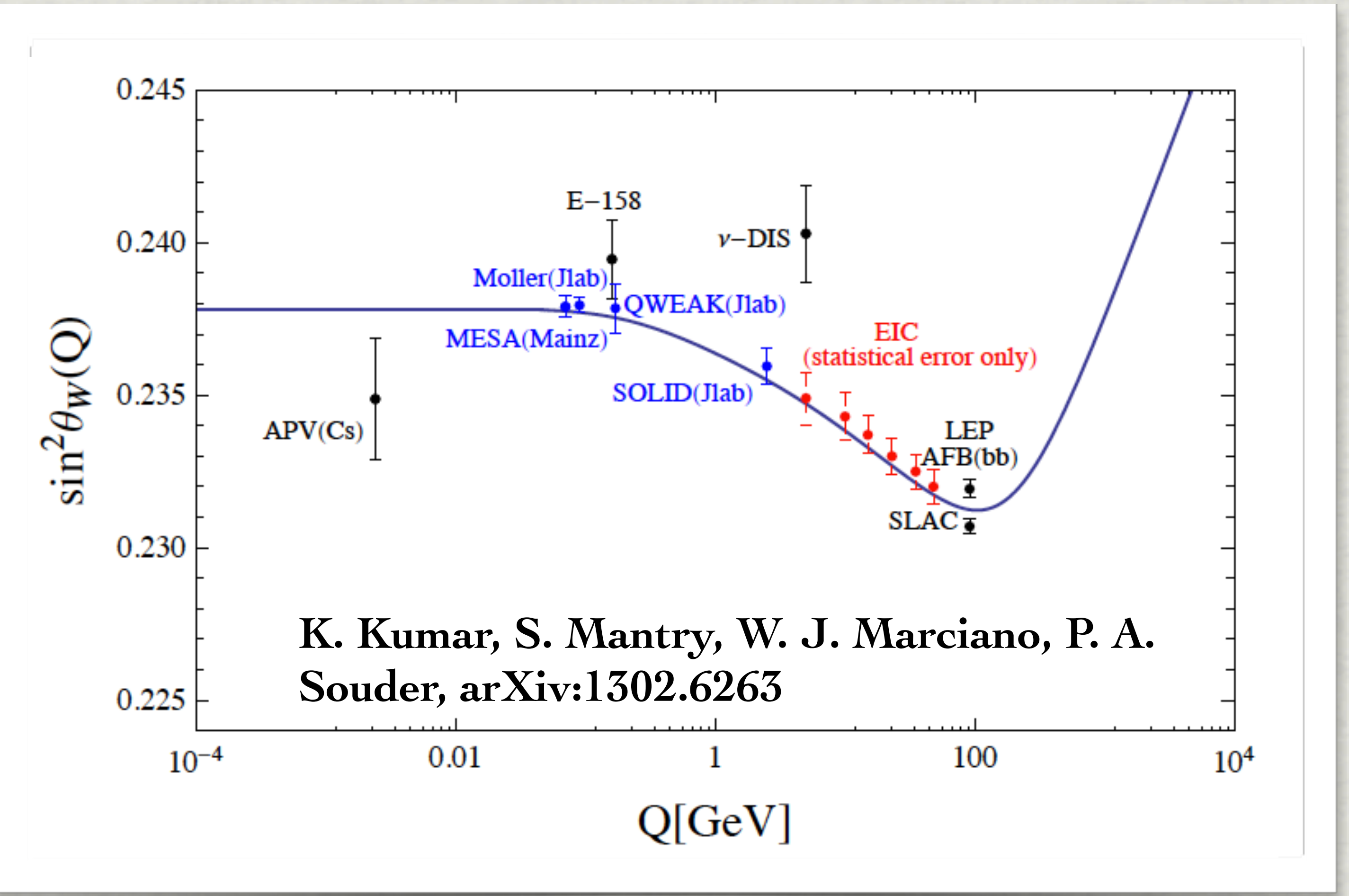




P. S. Barbeau, J. I. Collar, IEEE Trans.Nucl.Sci. 50 (2003) 1285-1289

Precision Test of the Weak Nuclear Charge

- Theory uncertainties on radiative corrections are small because we now know the M_{top} and M_{Higgs}
- Remaining hadronic theoretical uncertainties have similar magnitude as those from Atomic Parity Violation experiments (~0.2%) with different source



Precision Test of the Weak Nuclear Charge

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi}((G_V + G_A)^2 + (G_V - G_A)^2(1 - \frac{T}{E_\nu})^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2})$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

$$G_A = ((g_a^p + 2\epsilon_{ee}^{uA} + \epsilon_{ee}^{dA})(Z_+ - Z_-) + (g_a^n + \epsilon_{ee}^{uA} + 2\epsilon_{ee}^{dA})(N_+ - N_-))F_{nucl}^A(Q^2)$$

$$g_V^p = \rho_{\nu N}^{NC}(\frac{1}{2} - 2\hat{\kappa}_{\nu N} sin^2\theta_w) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR}$$

$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}$$

+ axial vector factors which have more theoretical uncertainty (strong quark contributions, weak magnetism term, effective neutrino charge radii)

Precision Test of the Weak Nuclear Charge

0) Use gas targets (swappable) to control fiducial volume systematics

1) Low q^2 @ Rx to avoid $F(q^2)$ form factor systematic uncertainties

2) eliminate axial couplings

→ Choose even-even nuclei

H_2	$^{32,34}SF_6$
$^{3,4}He$	CO_2
$^{10,11}BF_3$	$^{20,22}Ne$
$^{12,13,14}CH_4$	N_2
C_2H_6	$^{82,83,84,85,86}Kr$
C_4H_{10} …	$^{39,40}Ar$
CF_4	$^{129-132,134,136}Xe$

Precision Test of the Weak Nuclear Charge

3) Factorize out ν flux (~6%) & absolute rate uncertainties

→ group according Z=N & Z≠N & measure ratio: $\frac{R_{Z=N}}{R_{Z\neq N}}$

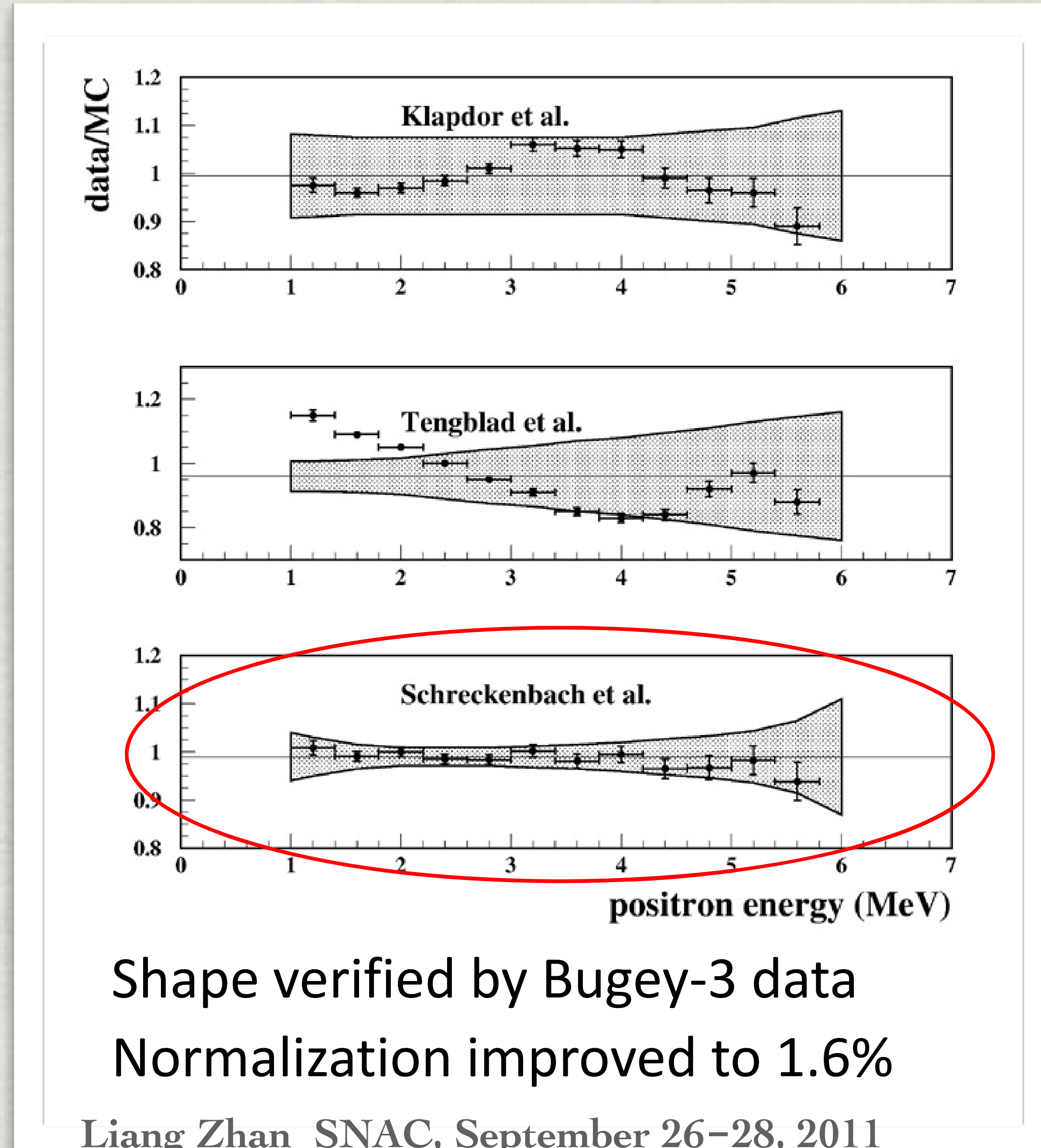
$$Q_{w,^4He} = 2 \times 4sin^2\theta_w$$
$$Q_{w,^{12}C} = 6 \times 4sin^2\theta_w$$
$$Q_{w,^{16}O} = 8 \times 4sin^2\theta_w$$
$$Q_{w,^{20}Ne} = 10 \times 4sin^2\theta_w$$

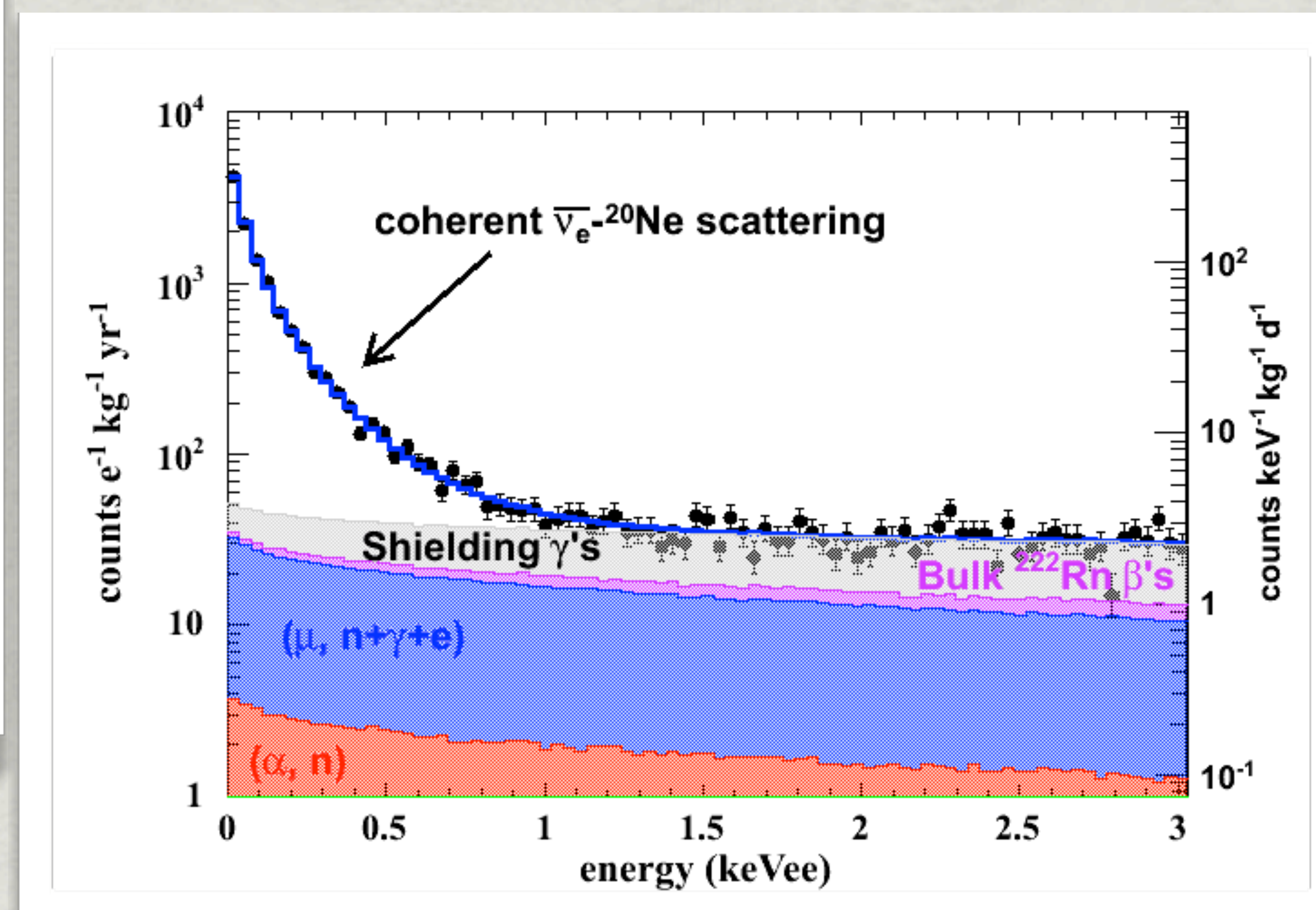
$$Q_{w,^{22}Ne} = 2 + 10 \times 4sin^2\theta_w$$
$$Q_{w,^{40}Ar} = 4 + 18 \times 4sin^2\theta_w$$
$$Q_{w,^{136}Xe} = 28 + 54 \times 4sin^2\theta_w$$

$$Q_w = N - (1 - 4sin^2\theta_w)Z$$

4) Use $A_1 \sim A_2$ nuclei to minimize impact of Rx neutrino spectrum uncertainties → **$^{20,\,22}$Ne**

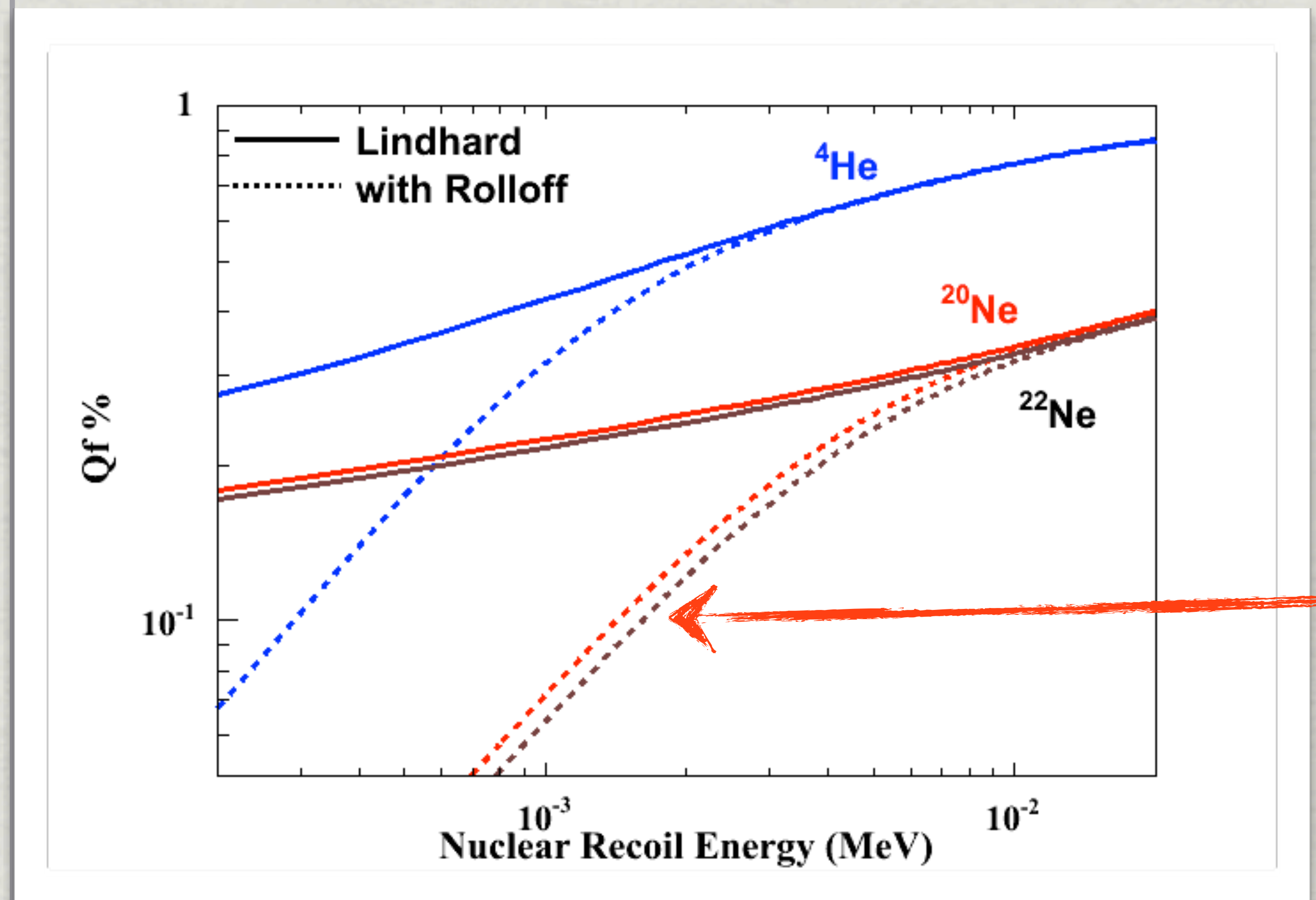
Choose recoil thresholds to select same population of ν energies (10% change between ^{20,22}Ne)





Quenching Factors

4.5) Choosing Ne also avoids atomic uncertainties for the quenching factor



Difference is predictable: Isotope effect has been well studied (e.g. ^{1}H-^{2}H, ^{22}Na-^{24}Na)

$$f_n \sim \frac{1}{A^{\frac{1}{2}}+1} \times (1 - e^{\frac{-E_r}{E_t}}); \quad E_t \sim A$$

J. A. Davies, J. D. McIntyre & G. A. Sims, Can. J. Chem. 39, 611 (1961)

J. Lindhard, M. Scharff, Phys. Rev. 124 (1) 1961 (references therin)

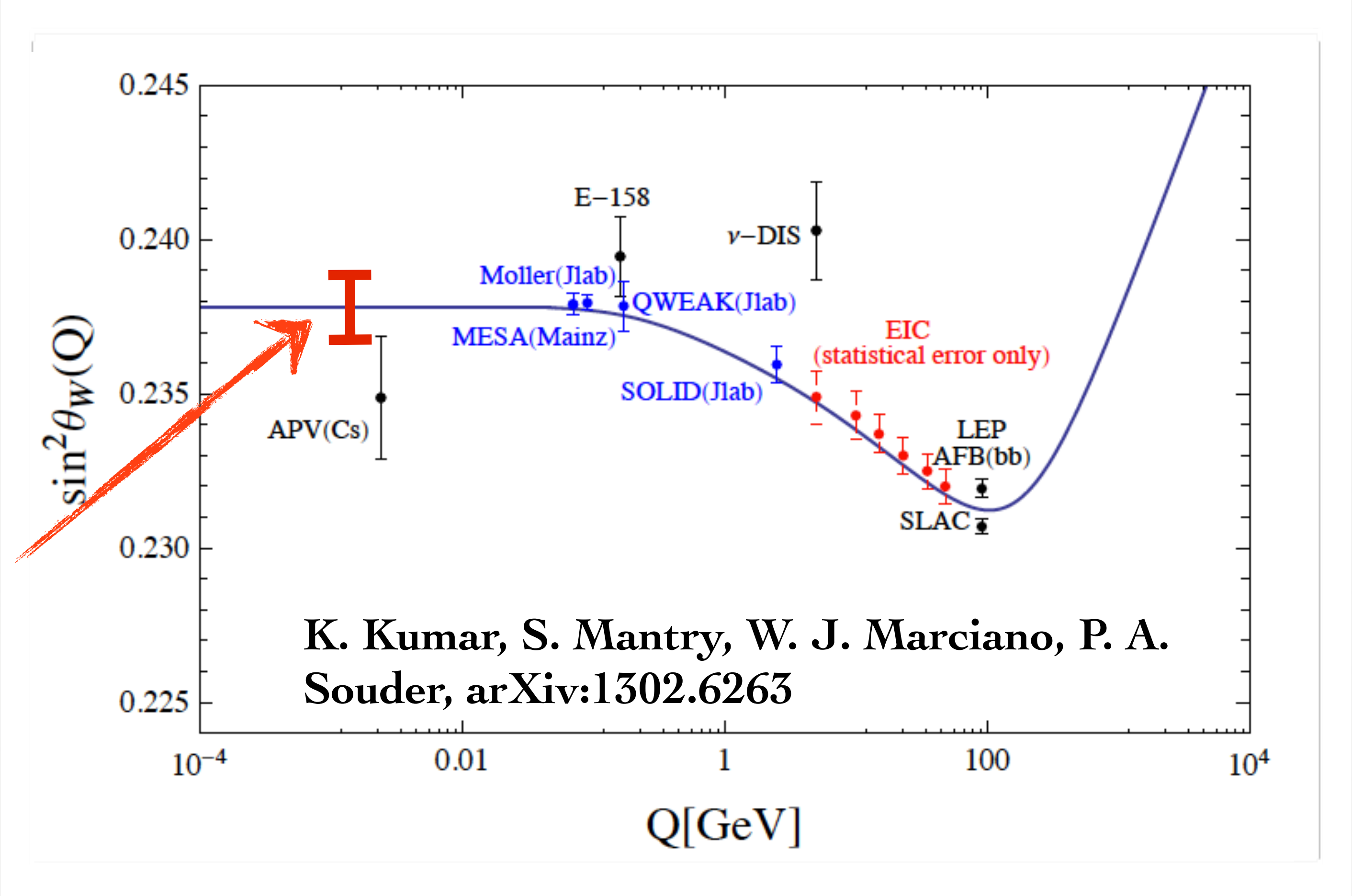
Precision Test of the Weak Nuclear Charge

- Run for 5 cycles at SONGS. One cycle is 18 months *ON*, one *OFF*
- Operate in both Tendon Galleries to maximize Rx OFF time. → 2 x 20 kg detectors at ~ 1-10 Bar
- Result → uncertainties on $\sin^2 \theta_W$:

±0.22% (stat.) ±[0.1]% (sys.) ± <0.2 (th.)

$$R(\frac{^{22}Ne}{^{20}Ne}) = \frac{(2 + 10 \times sin^2\theta_w)^2}{(10 \times sin^2\theta_w)^2}$$

$$\sigma(sin^2\theta_w) = 0.57 \times \sigma R$$

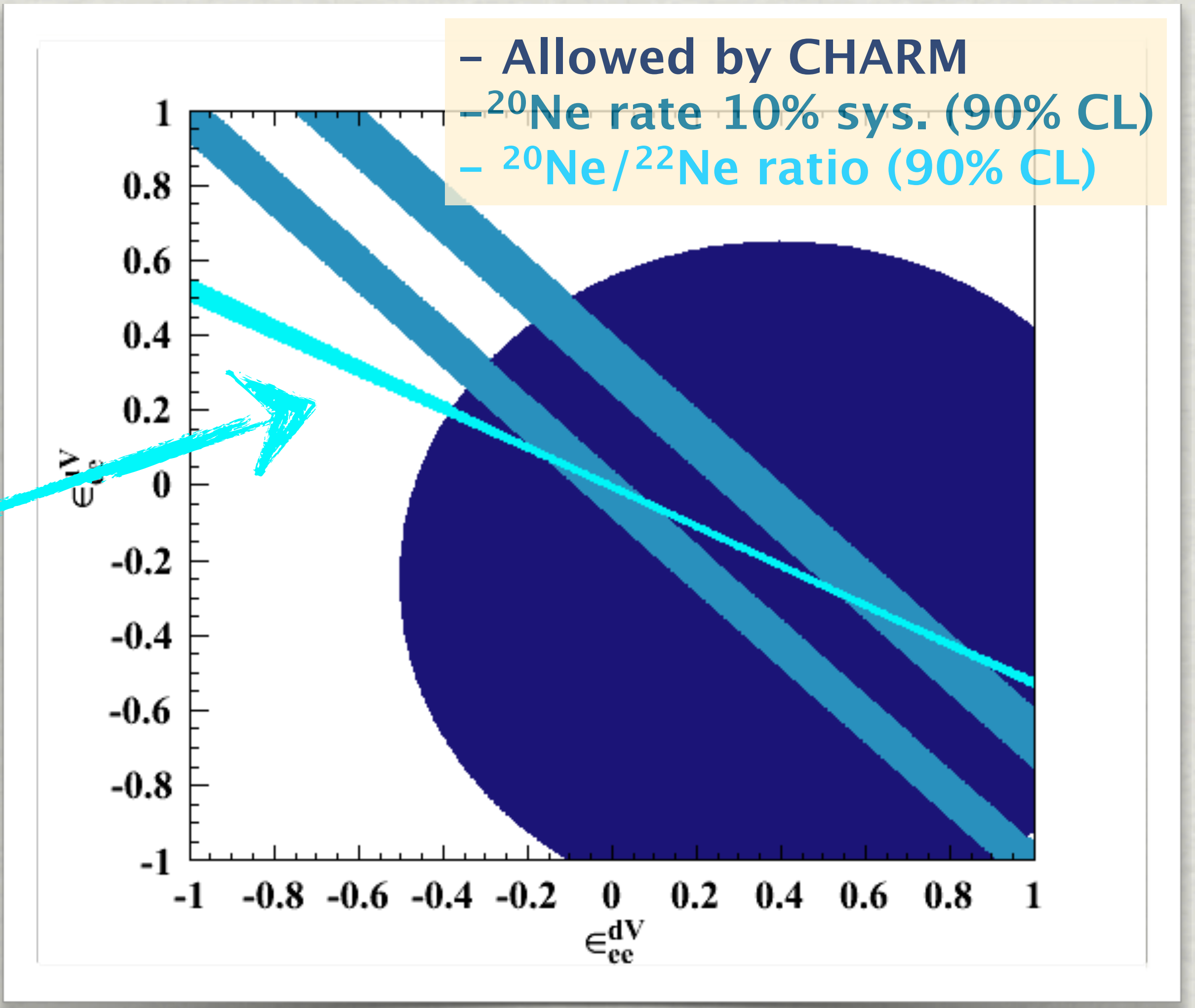


Gratis: NSI Search with Neon

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi} = G_V^2(1 + (1 - \frac{T}{E_\nu})^2 - \frac{MT}{E_\nu})$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

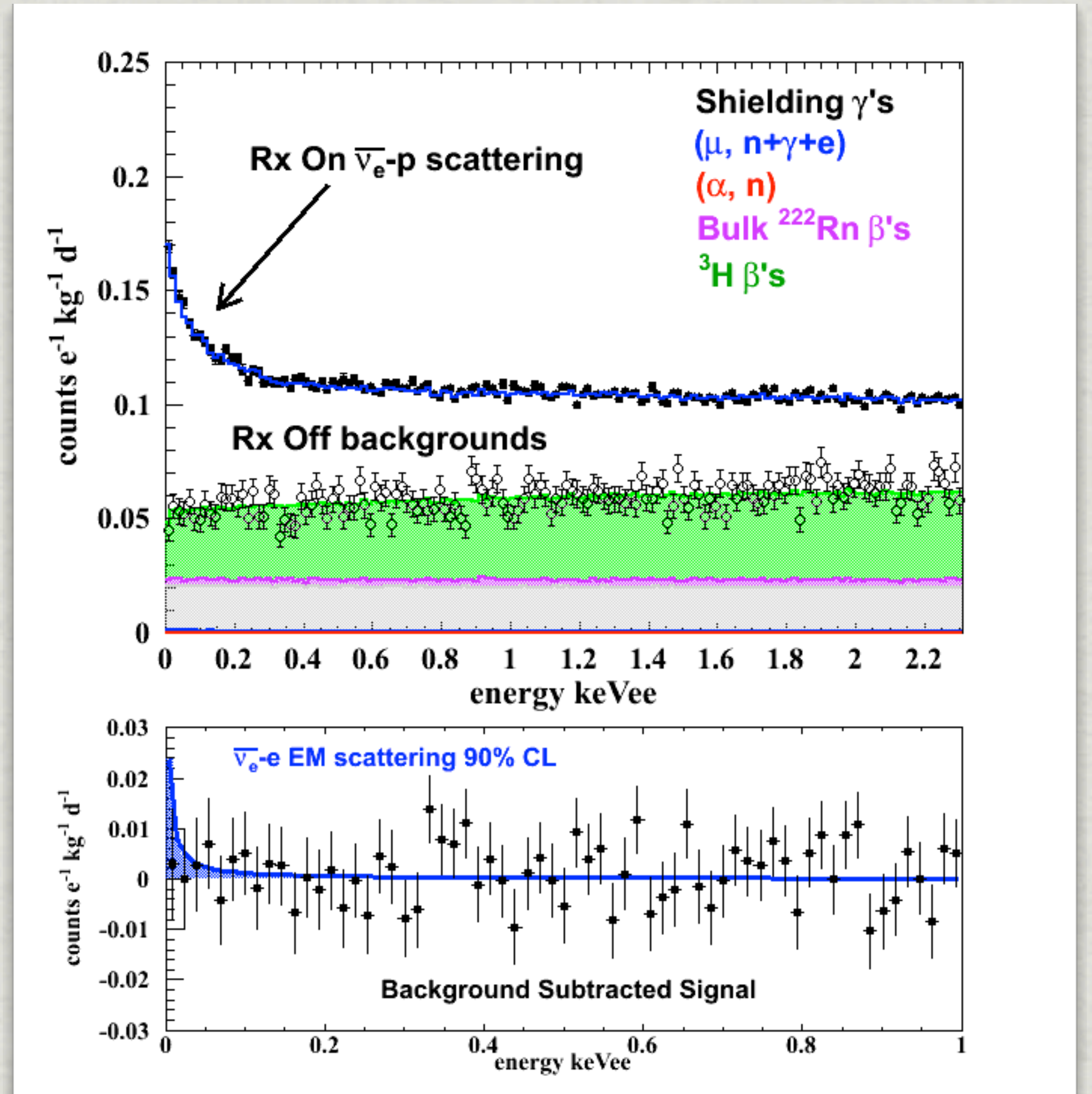
- We take advantage of the precision in the $^{20}Ne/^{22}Ne$ system
- If we include the SM radiative corrections, as well as statistical & systematic uncertainties, the ratio of the interaction rates for $^{20}Ne/^{22}Ne$ gives

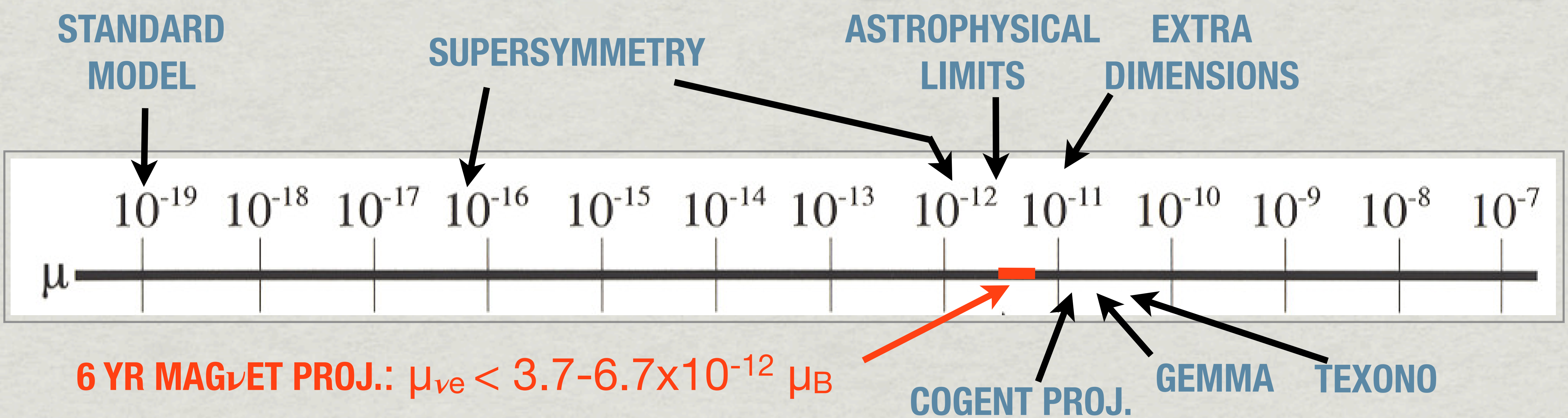


also see: K. Scholberg Phys.Rev.D73:033005,2006

H_2 μ_ν Search

- Pro: H_2 minimizes impact of Rx ON backgrounds from ν-nucleus scattering
- Con: ^3H background requires De-tritiation
- Uncertainties: Rx off stat., 10% QF & Rx ν flux





6 YR MAGνET PROJ.: $\mu_{\nu e} < 3.7\text{-}6.7 \times 10^{-12}\ \mu_B$

MAGν_eT is information rich

- Like CoGeNT, use MAGν_eT for a short baseline $\nu_{sterile}$ search

- Precision tests of the weak nuclear charge and NSI

- *Probe of Nuclear Density Distributions (Form Factors) at SNS

- *Neutrino cross-section measurements on various targets: H_2, CH_4, CF_4, ^3He, D_2, BF_3 (axial couplings to unpaired neutrons and protons, weak magnetism)

- Neutrino magnetic moment searches

- *caveat emptor*: **coherent ν scattering has to be discovered along the way**

- *Gratis*: **Positioned to bring clarity to Dark Matter Direct Detection picture**

To Conclude

-The coherent scattering of weakly interacting particles off nuclei has long been prophesied to test physics beyond the standard model

-The day is approaching (and may be here) when detectors that were designed to discover low energy neutrino & Dark Matter interactions will need higher precision: <u>extraordinary claims & extraordinary evidence</u>

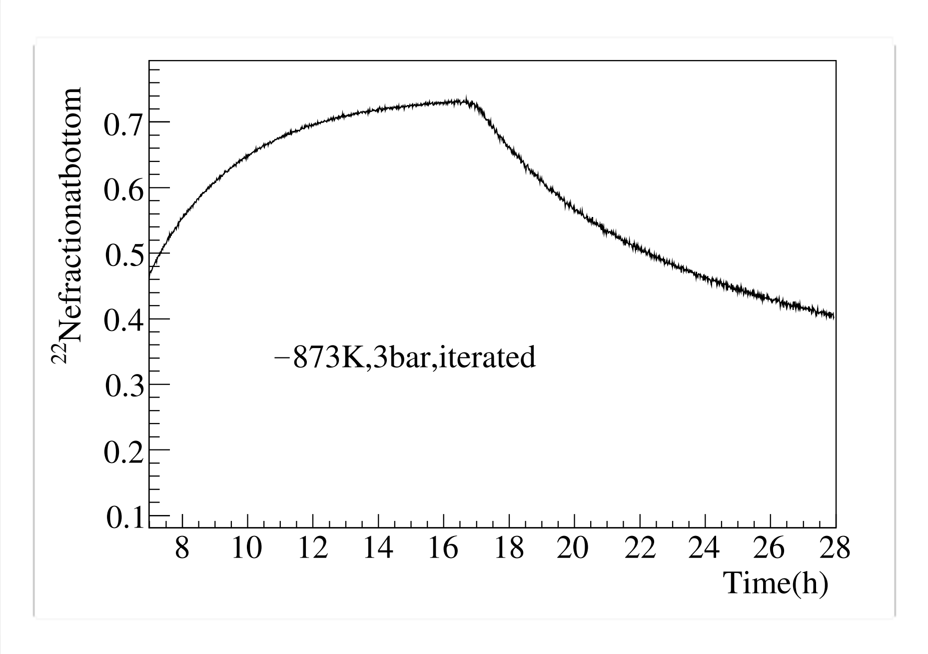
-A detector concept has been presented which builds upon past success for these applications, and which focuses on eliminating systematics with a simple, robust technology for precision experiments

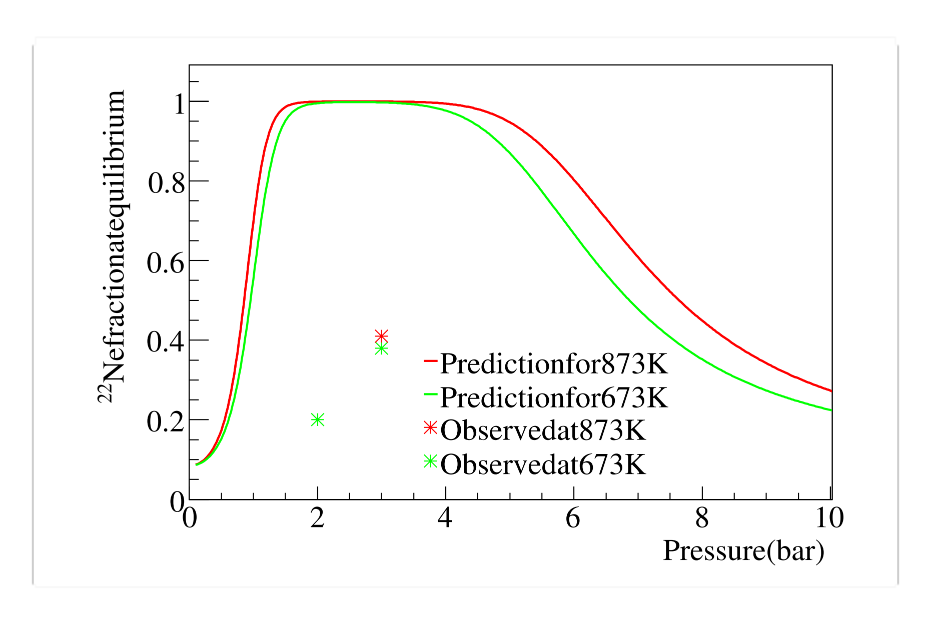
YET ANOTHER COGENT SEARCH
(FOR BNC CONNECTORS)

Backup Slides

Thermal Columns: Neon enrichment

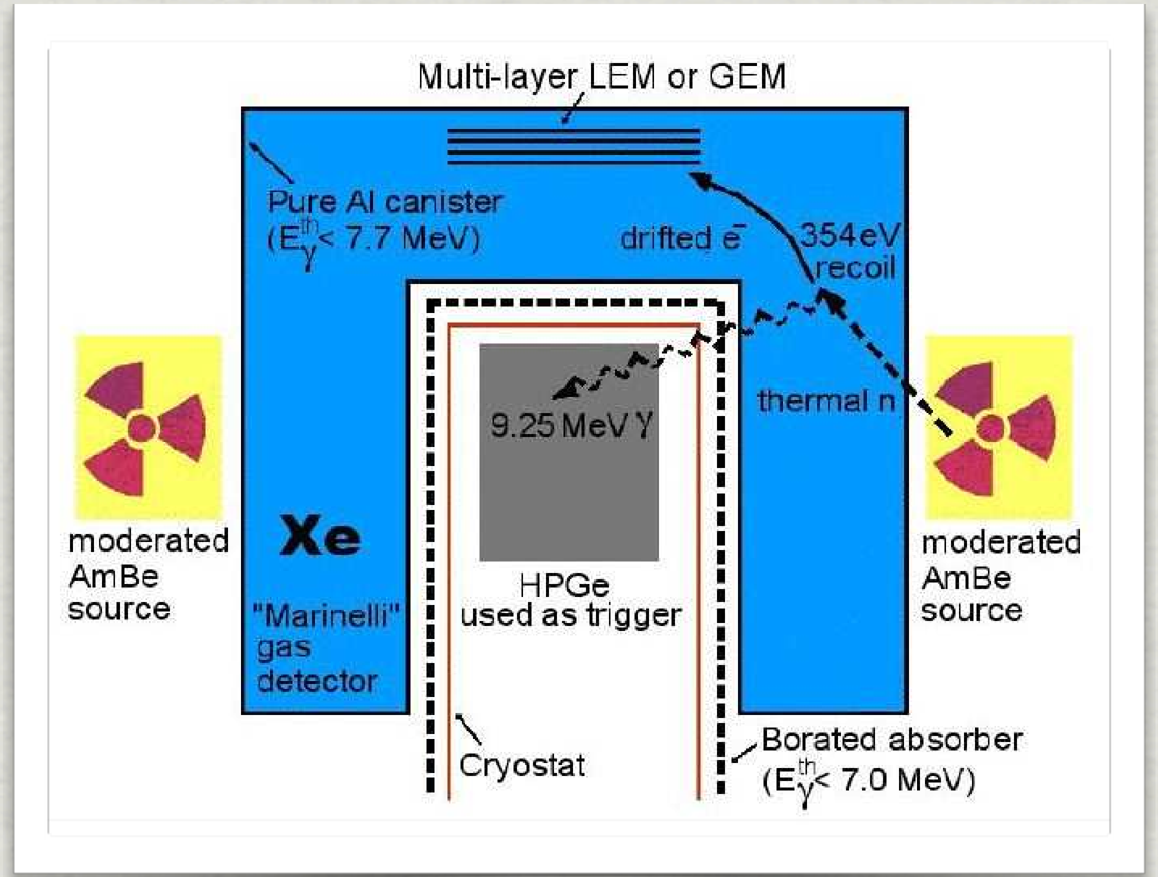
- The Yale group have demonstrated the partial enrichment of ^{22}Ne using thermal columns
- see H. Lippincott, PhD. Thesis, Yale University
- Two hypotheses are postulated that may explain the shortfall of the enrichment fraction w.r.t theory, which may have straightforward solutions

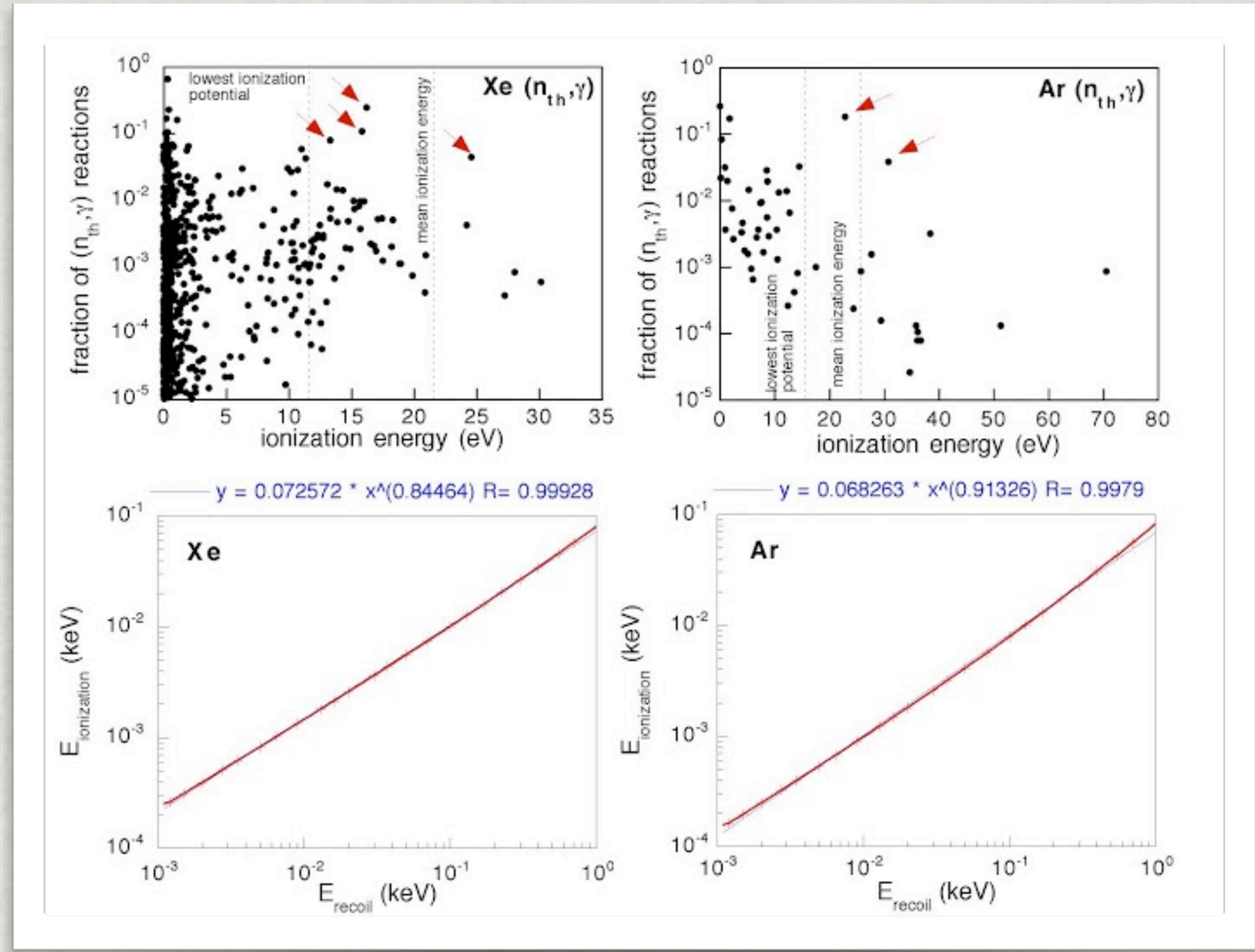




Quenching Factors

- Other methods probing extremely low energy recoils (from gamma emission) possible as well

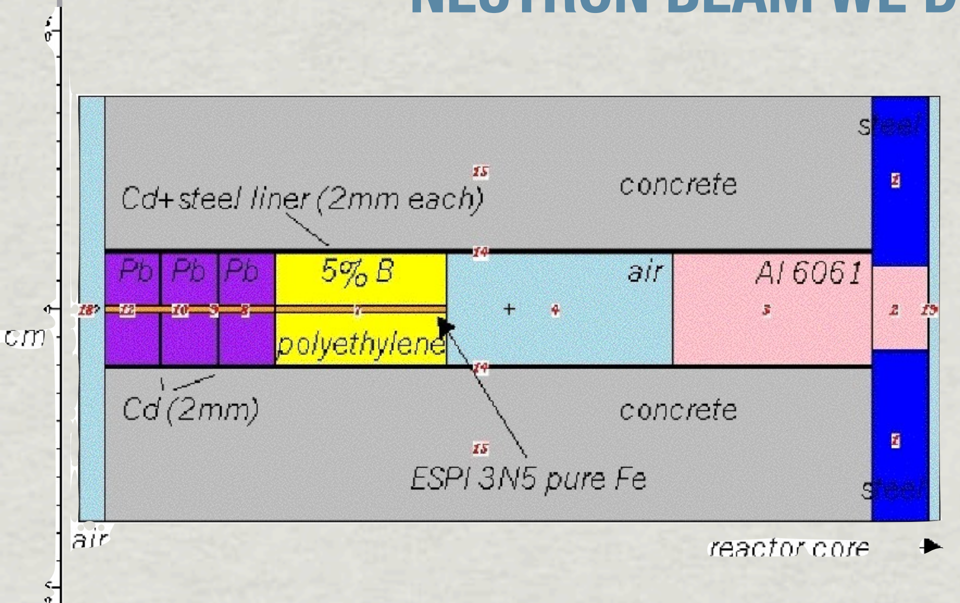


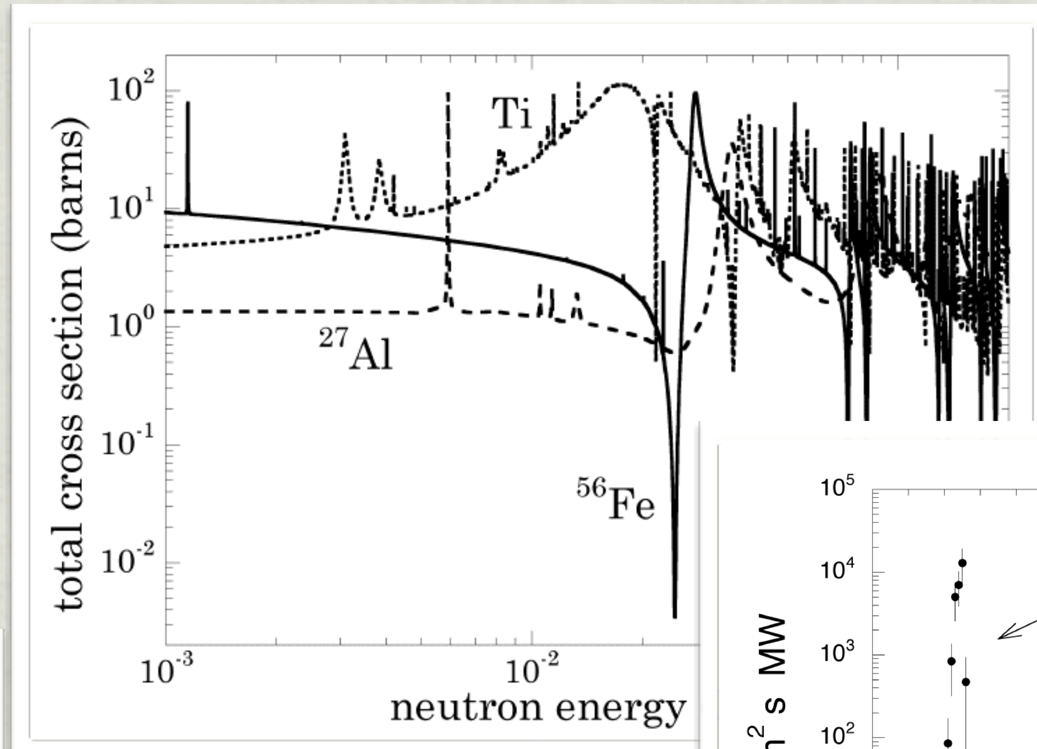


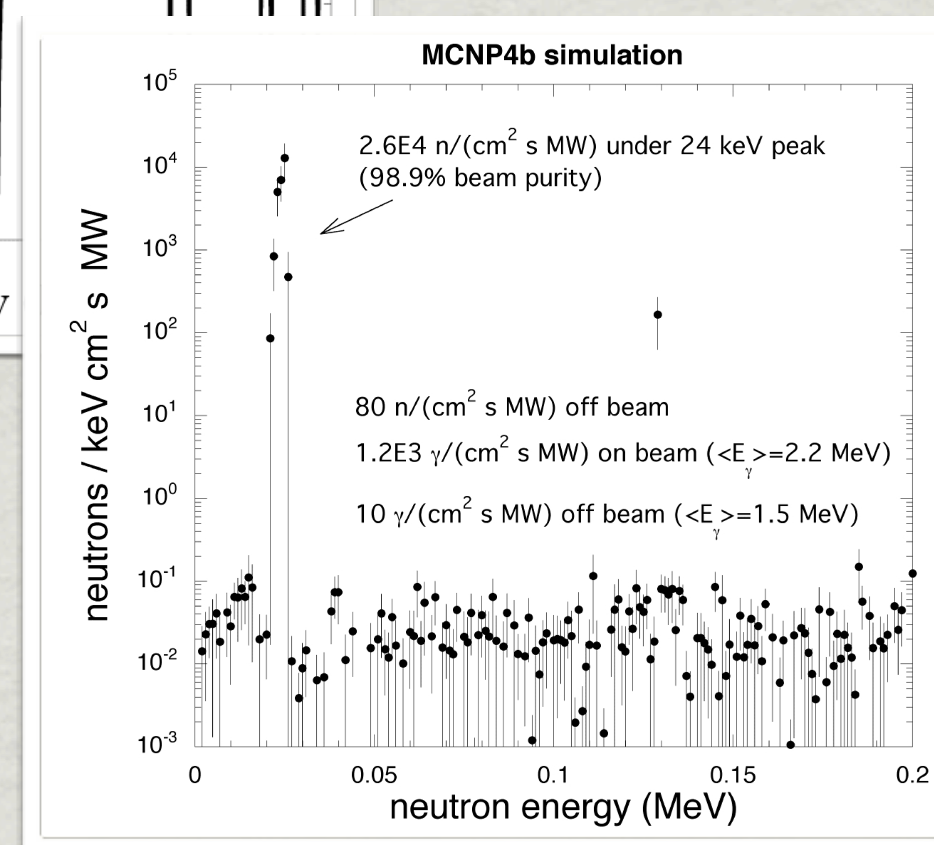
P. Barbeau, J. I. Collar, J. Miyamoto, and I. Shipsey. IEEE Trans. Nucl. Sci., 50:1285–1289, 2003.

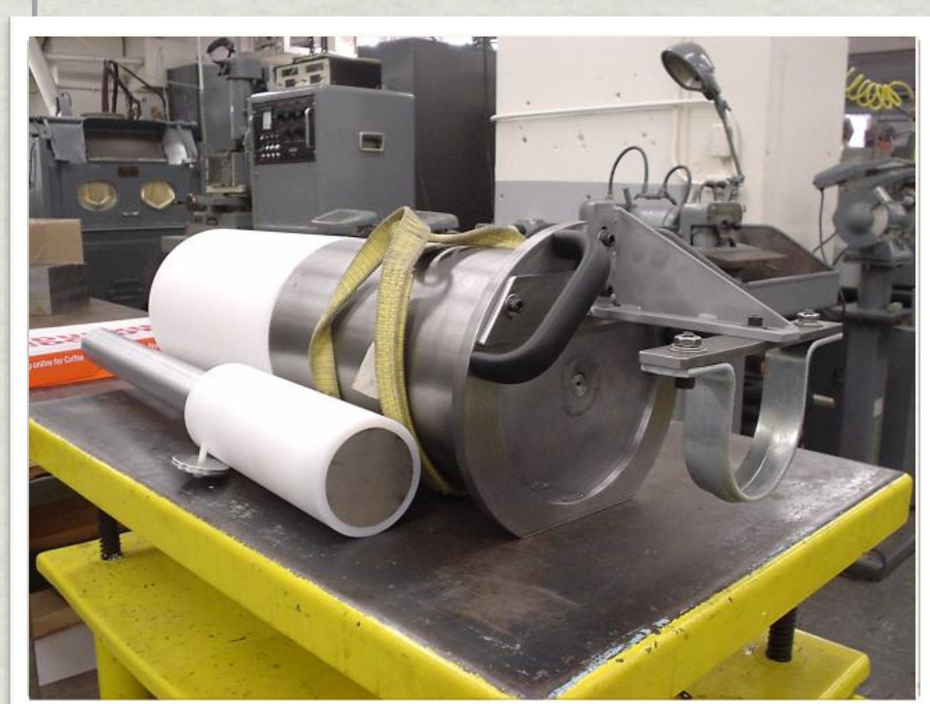
Quenching Factor Measurement

- **QUENCHING FACTOR: THE FRACTION OF THE NUCLEAR RECOIL ENERGY THAT GOES INTO IONIZATION.**
  - ~20% IN HPGE SEMICONDUCTOR DETECTORS
  - WITH PPC: MEASURED QF FOR LOW ENERGY NUCLEAR RECOILS USING 24 KEV NEUTRON BEAM WE DEVELOPED AT KSU TRIGA RESEARCH REACTOR



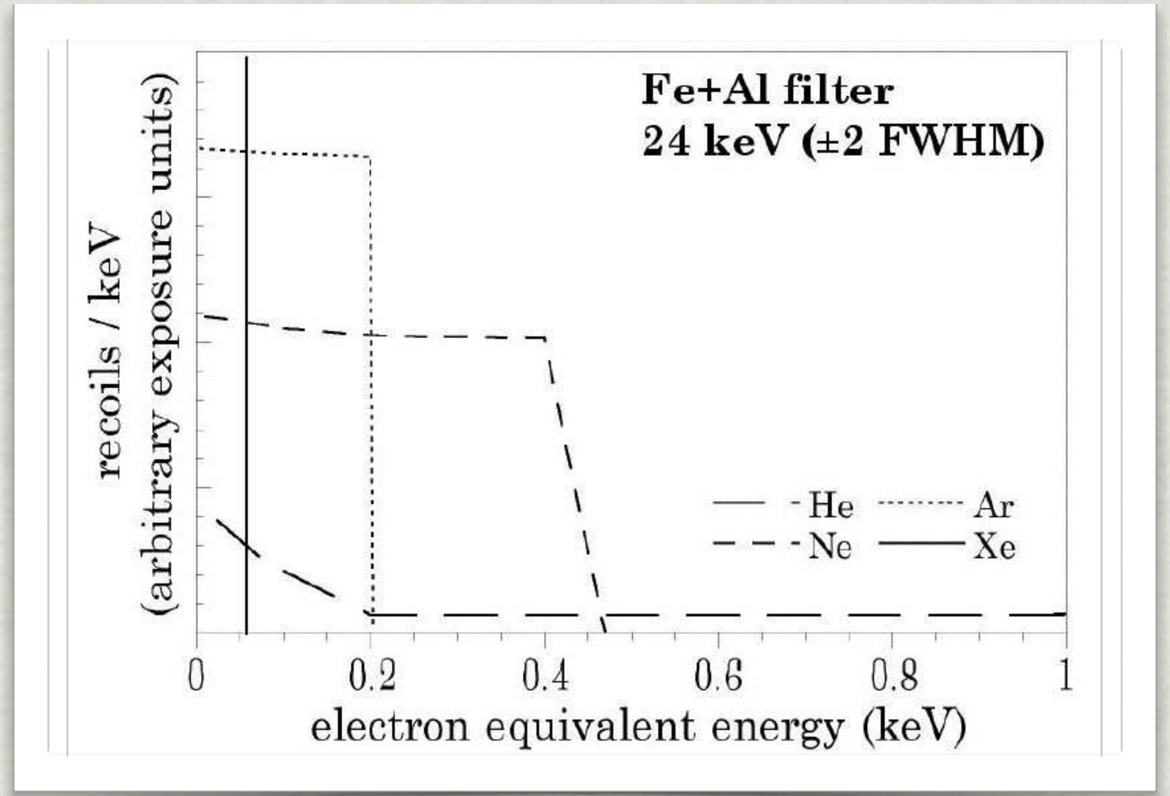




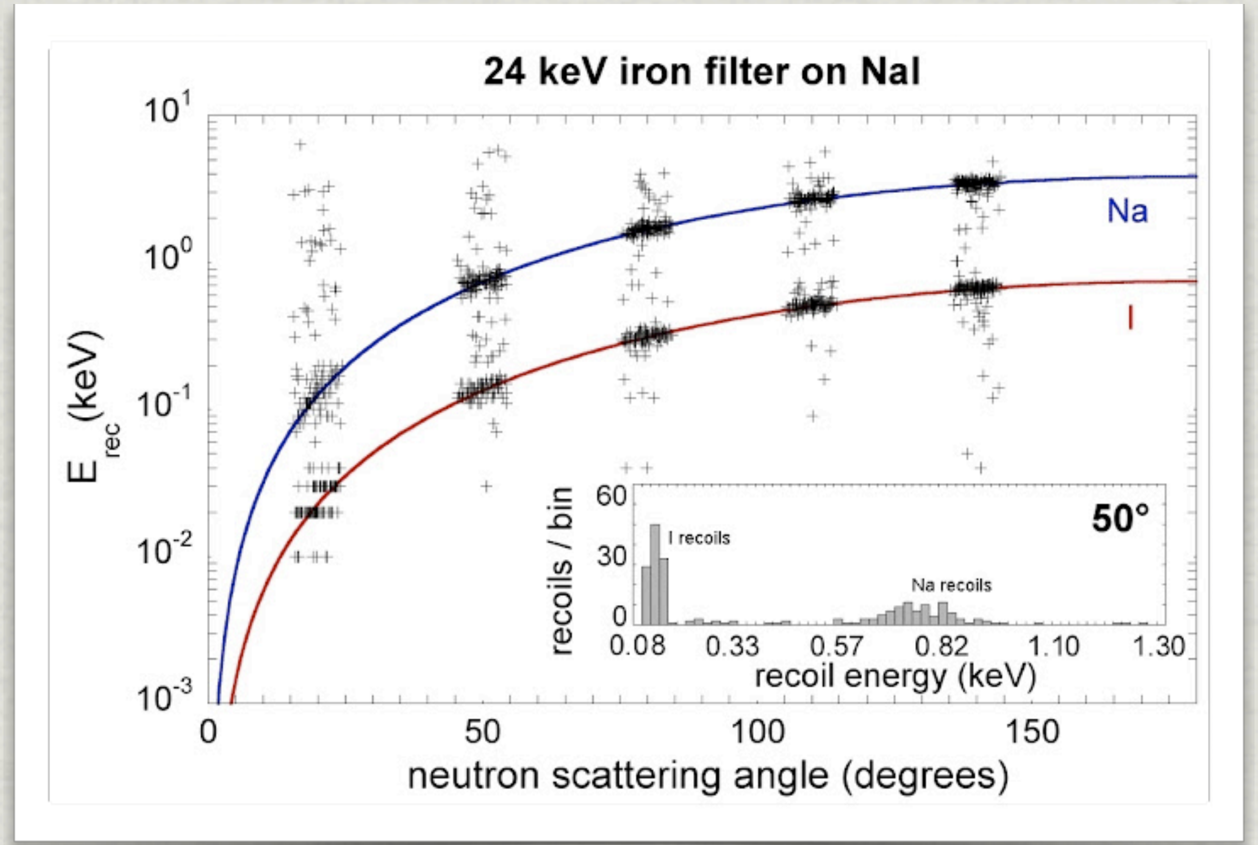


Quenching Factors

- Use COGeNT's 24 keV neutron beam to mimic the Rx ν's



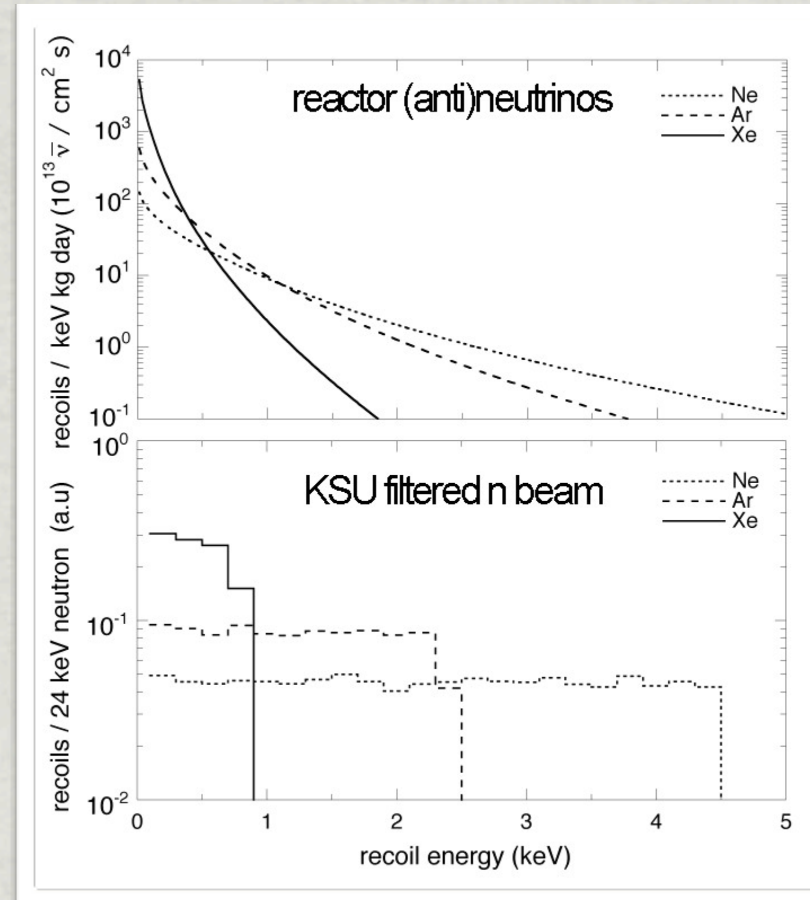
P. Barbeau, J. I. Collar, J. Miyamoto, and I. Shipsey. IEEE Trans. Nucl. Sci., 50:1285–1289, 2003.

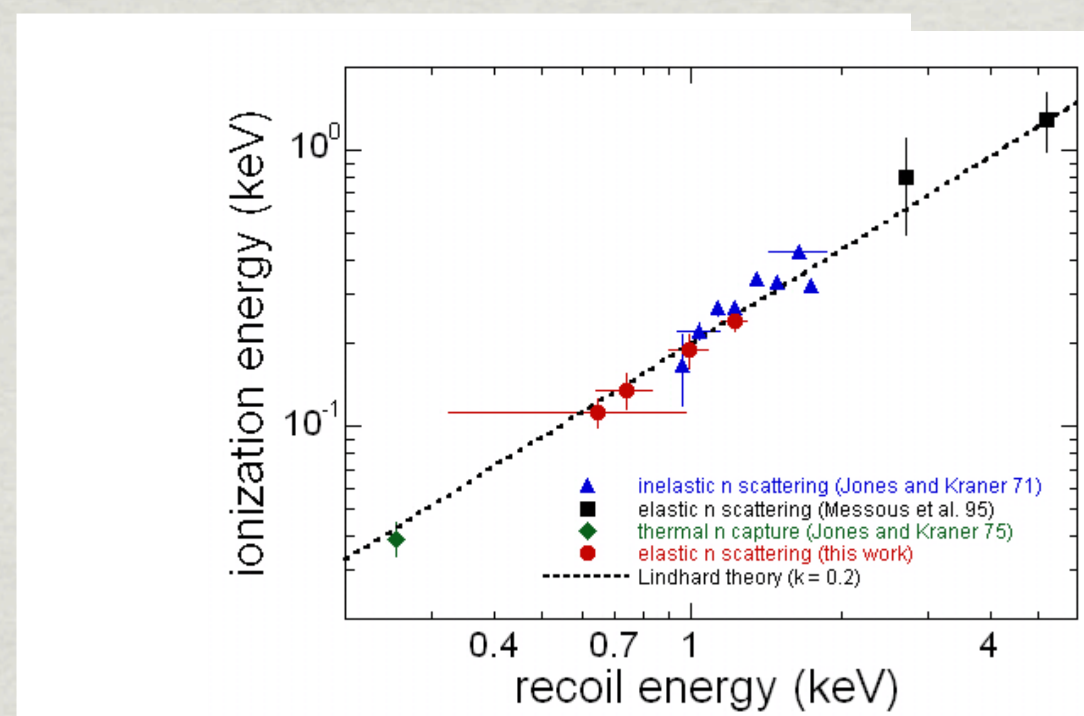


P. Barbeau, J. Collar, and P. Whaley. NIM. A, 574(2):385 – 391, 2007

CoGeNT: Importance of Calibrations

- Low energy nuclear recoils only deposit a fraction of their energy in the form of ionization (e.g. Quenching Factor ~ 20% for germanium)
- Developed a monochromatic 24 keV neutron beam at the KSU TRIGA reactor
- These neutron recoils mimic those expected from Rx ν's
- 10% uncertainty good enough for first measurement, but not for precision physics



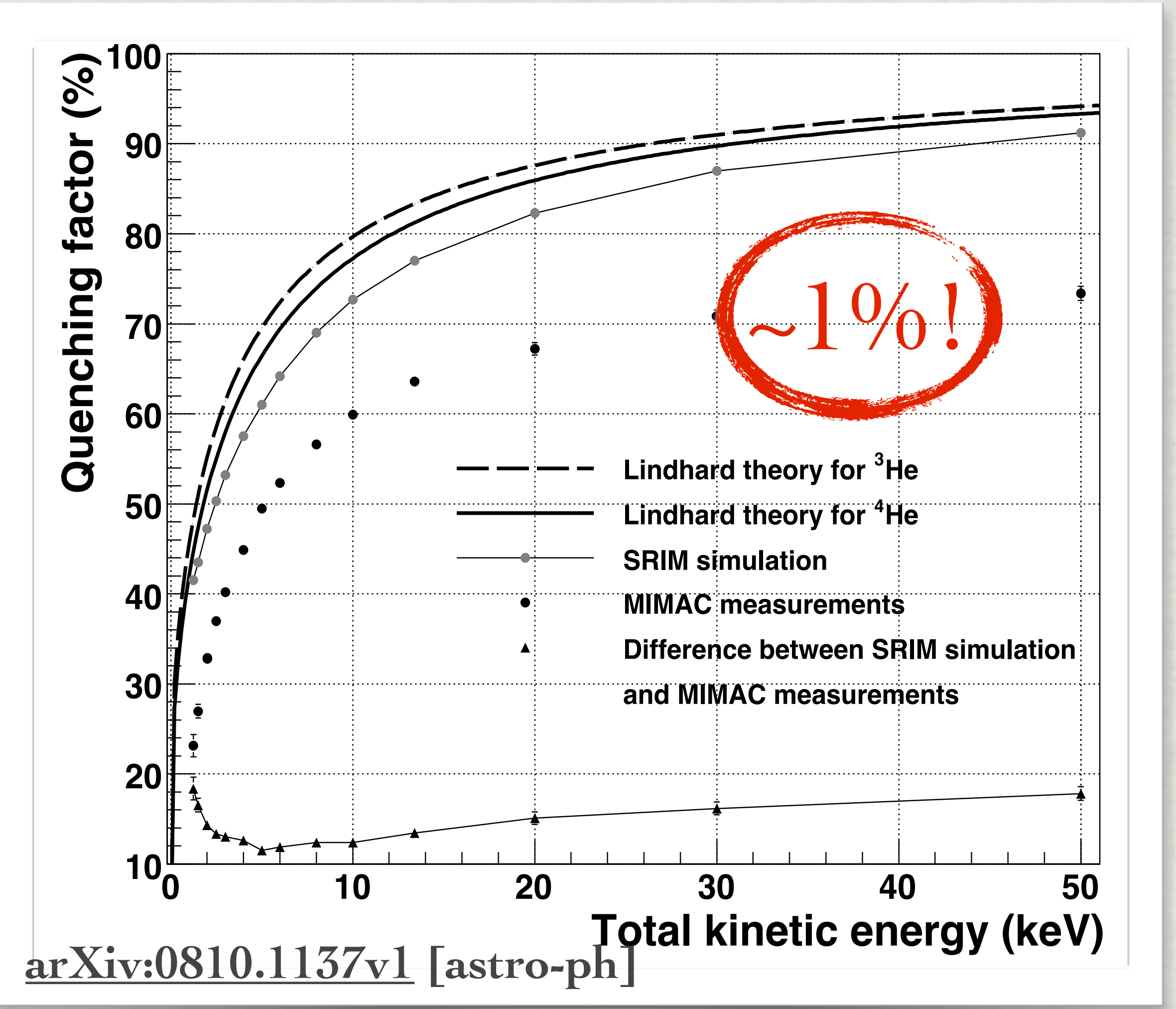


P. S. Barbeau, J. I. Collar, Nucl.Instrum.Meth. A574 (2007) 385-391.
P. S. Barbeau, J. I. Collar, and O. Tench., JCAP, 2007(09):009, 2007.

Quenching Factors

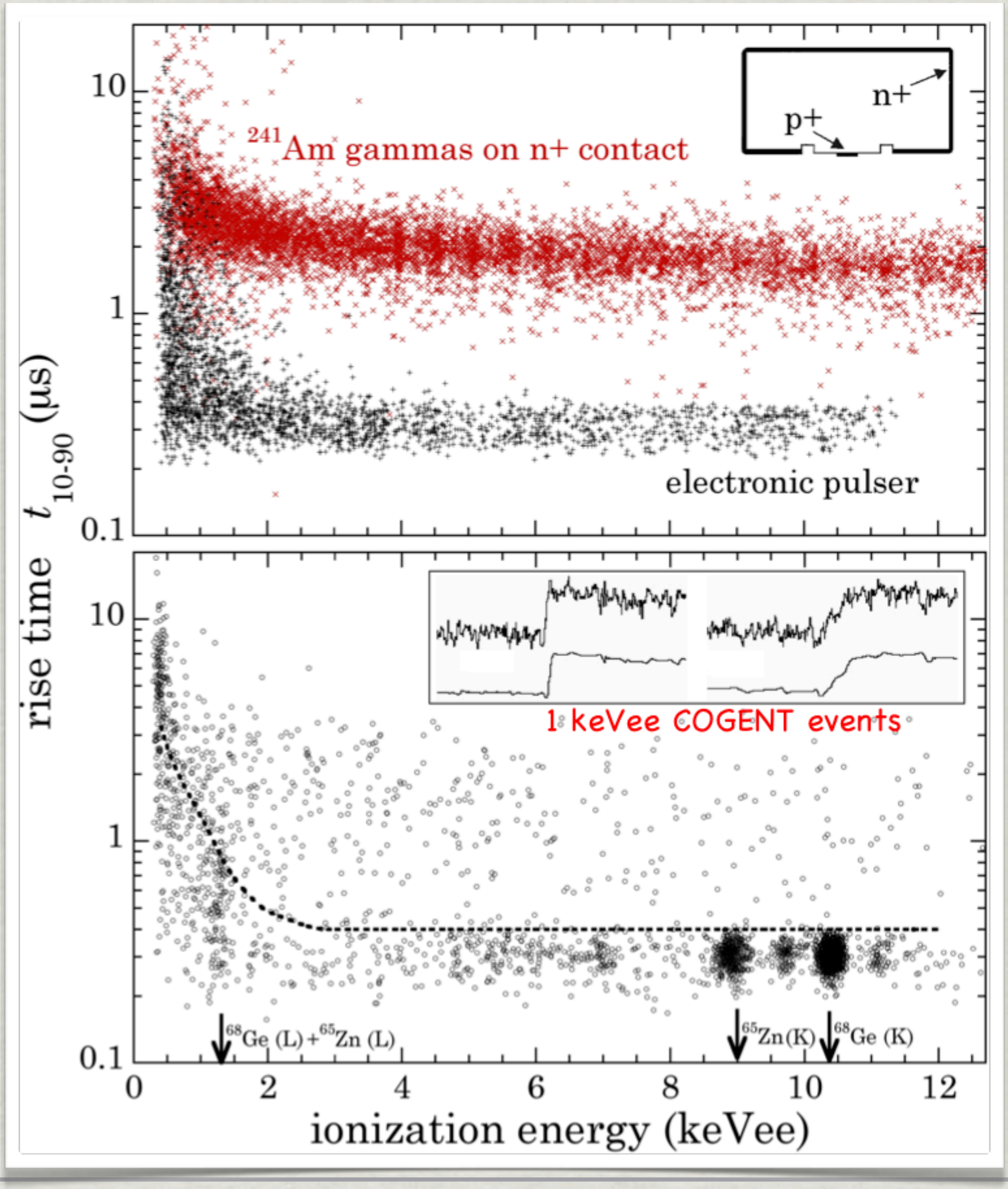
He recoils (MIMAC)

- High Precision measurements of the quenching factor have been demonstrated by other groups for gas detectors
- *The same 24 keV neutrons will mimic the recoils that would be produced from coherently scattered Rx ν's*



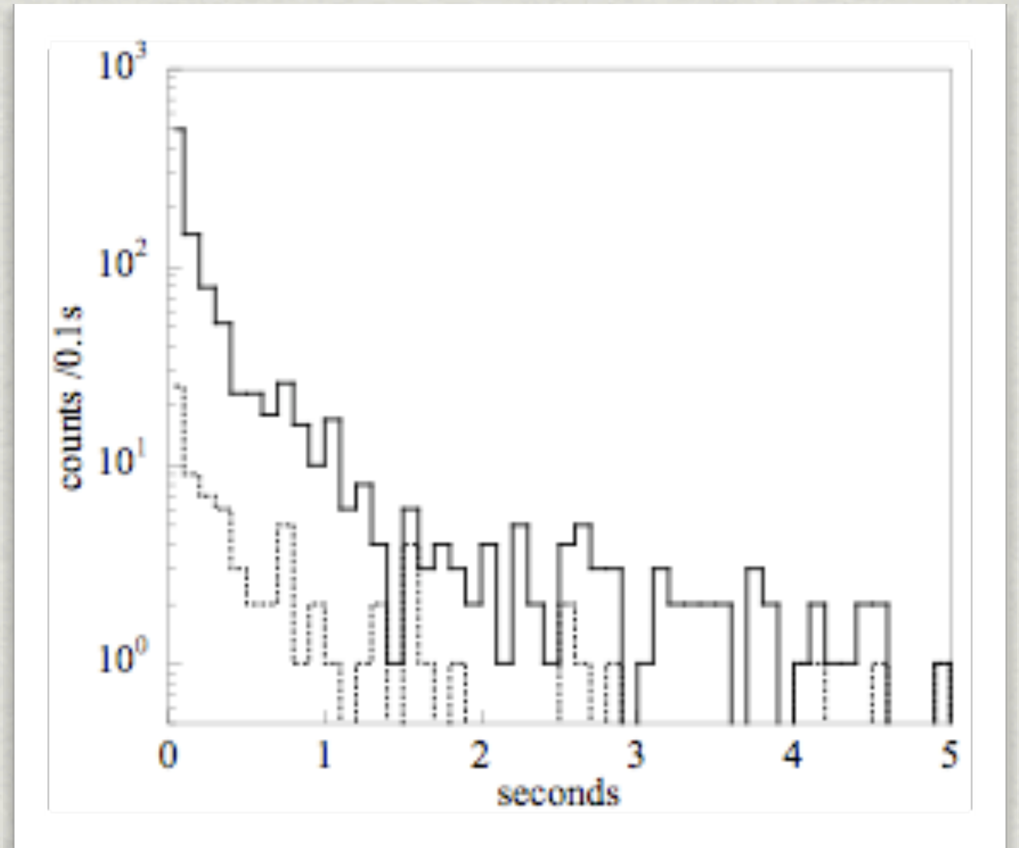
Trying to get lower background

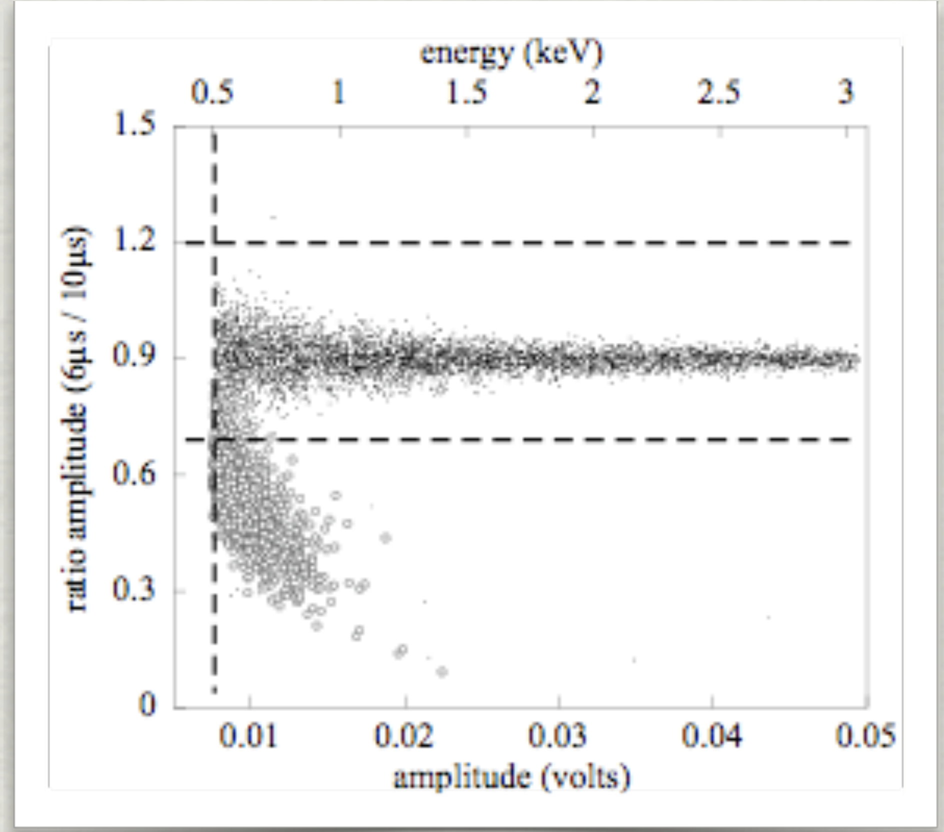
- At SONGS observed partial charge collection signals from ^{71}Ge K-shell
- At Soudan: discovered “slow” pulses
- At Chicago: Figured out that these are surface events
- And so we apply a cut (based, in part, on weighting field simulation of crystal)

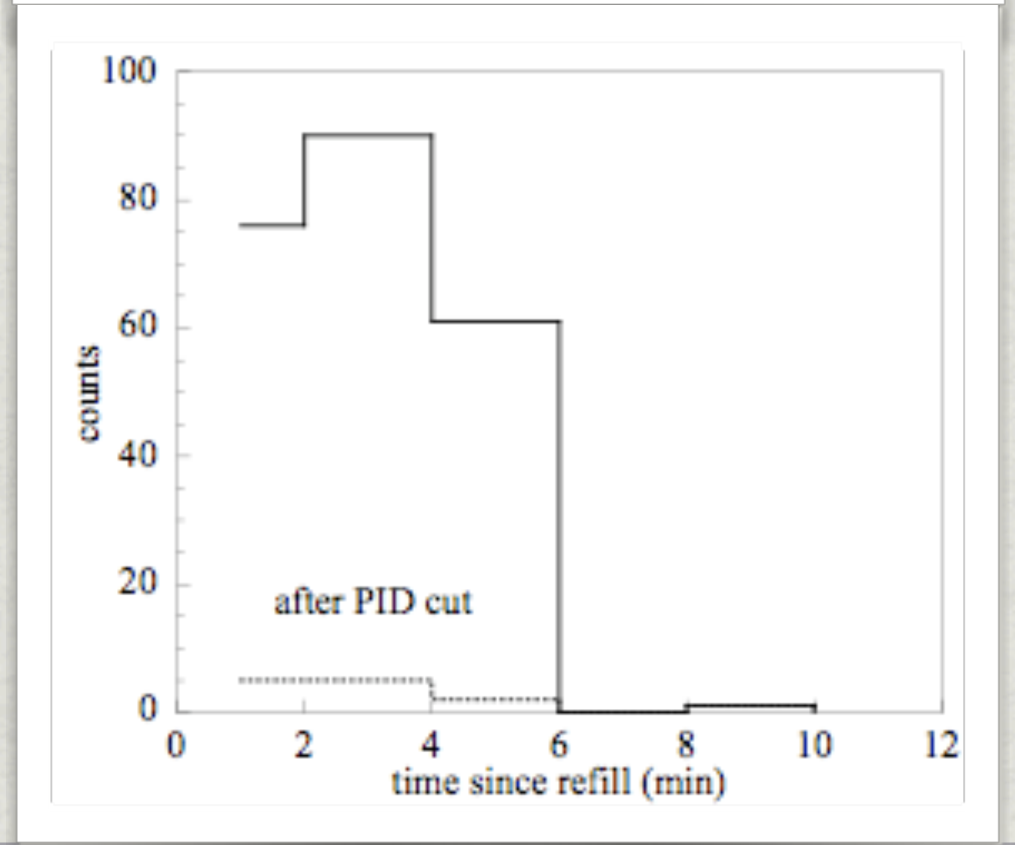


Microphonics PSD

- Reject microphonics using standard technique from Morales: (ratio of amplitude of two shaped pulses with different characteristics times)
- Bunching (in time)
- LN2 refills

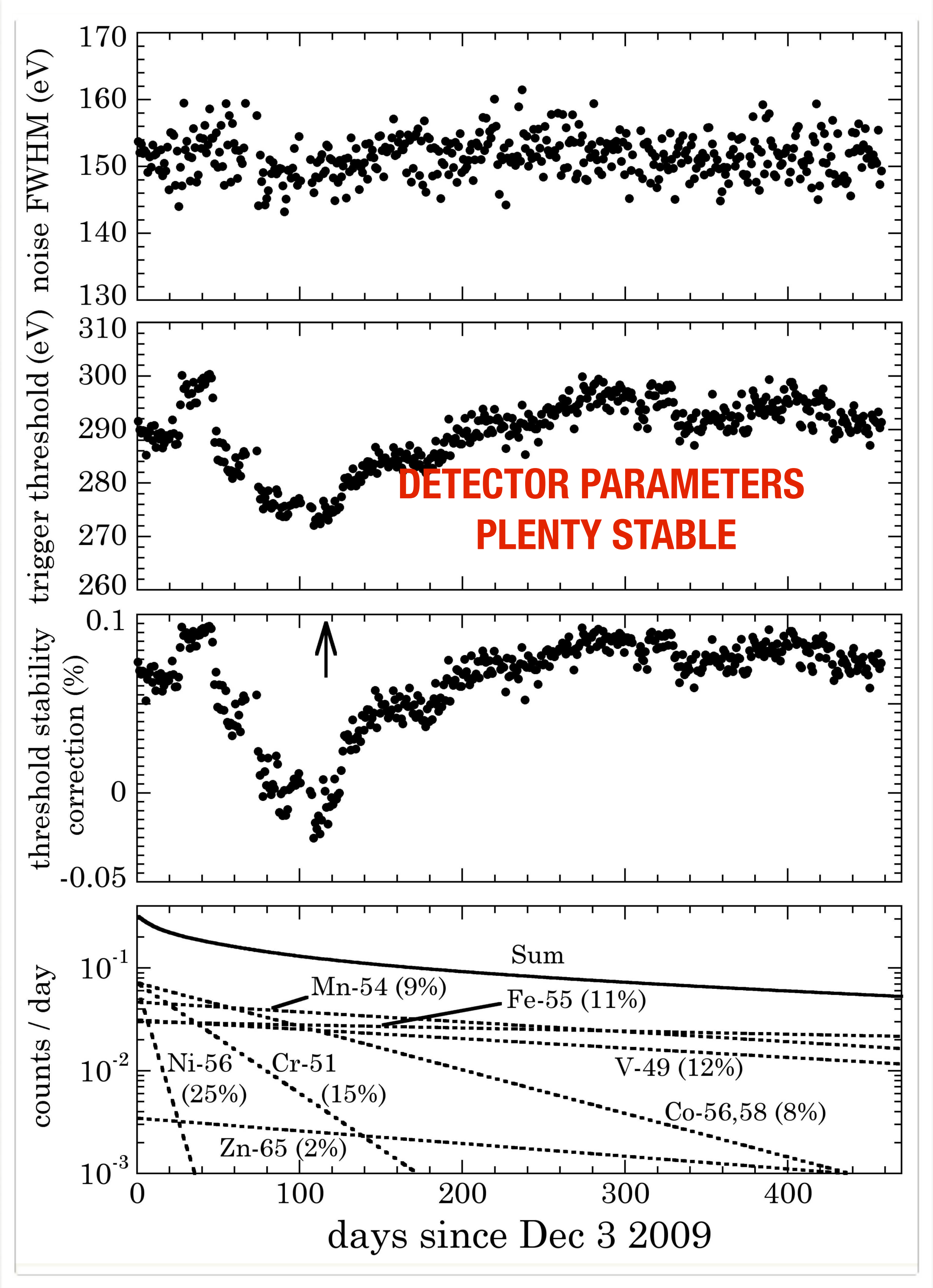






A fire and a 2.8σ hint of a modulation

- Fire in Soudan Lab March 17th of this year
- Everything survived
- incident triggered data analysis...just in case
- 458 days (442 live)
- Strip low-E Spectrum of L-Shell peaks (using assiciated K-Shell peaks)
- Account for decays of cosmogenically activated peaks



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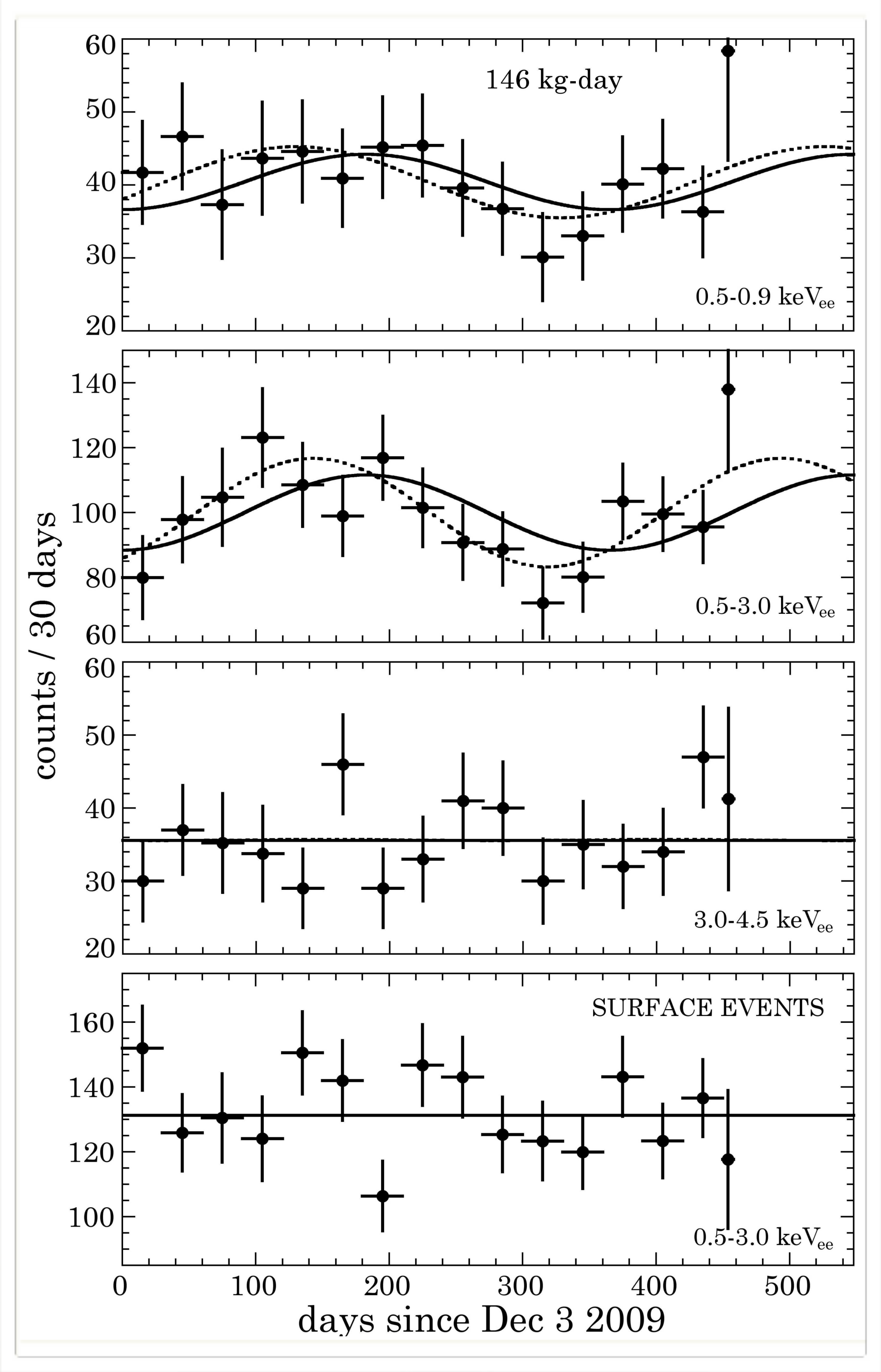
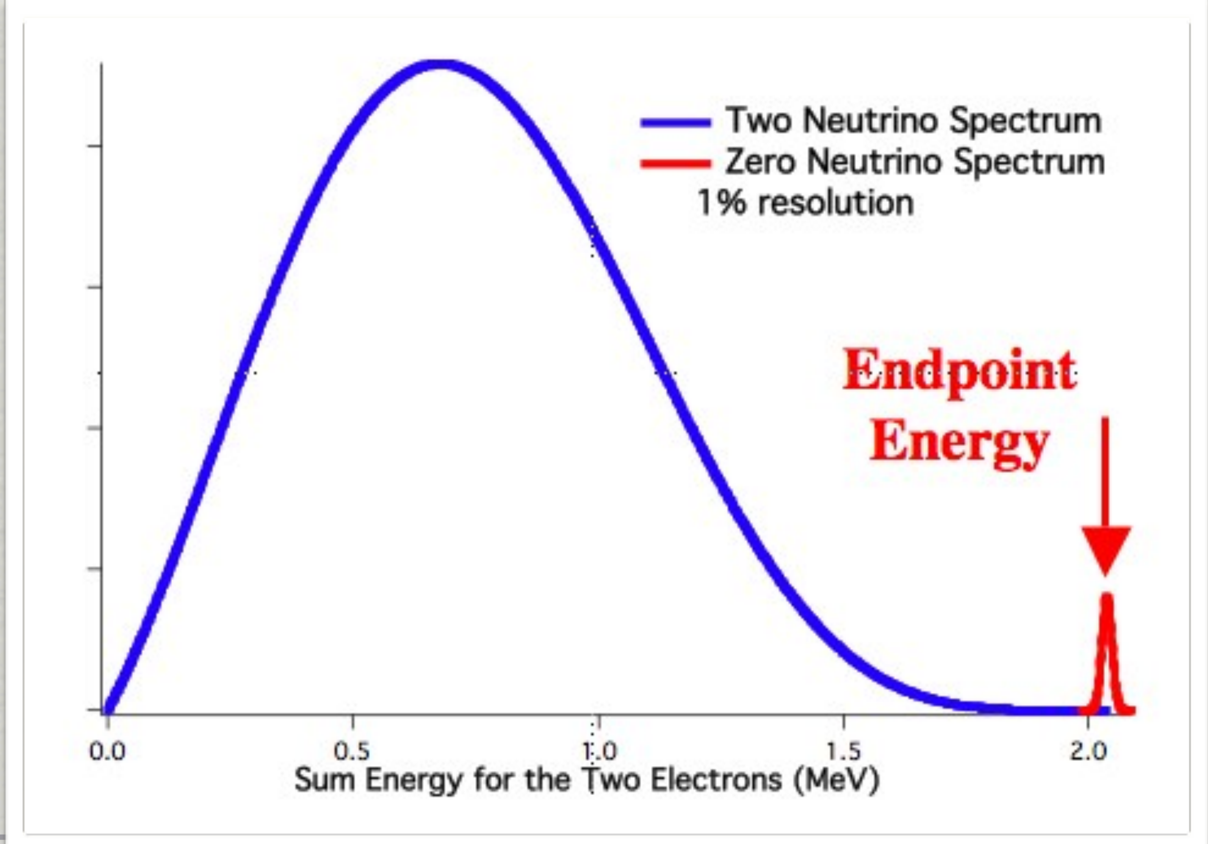
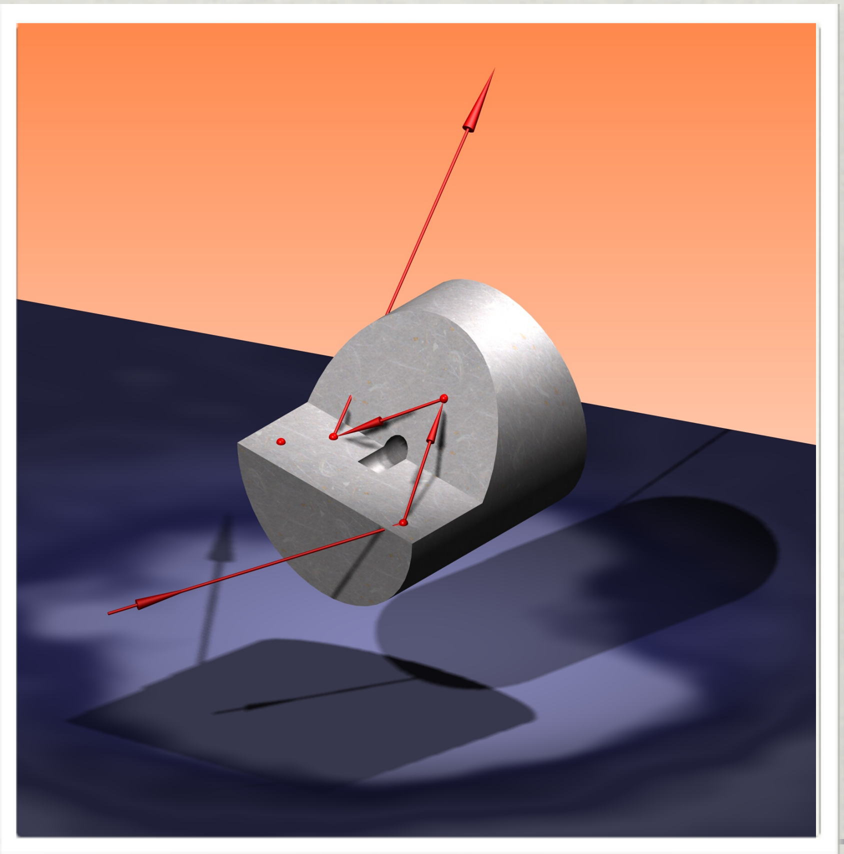
- Modulation signal at 2.8σ (cross-checked by many others after data shared)



The role of PPC detectors in the Majorana 0νββ experiment

- Source and target are the same…enriched ^{76}Ge HPGe
  - Signal peak at 2039 MeV single site 0νββ interaction
- The name of the game is background suppression
  - ΔE of Ge detectors limits ROI (0.16%)
  - clean materials (HPGe, underground electroforming of Cu, etc.)
  - reject Compton-scattered photon backgrounds: >1 crystal interaction (Granular cut)
  - PSD rejects multiple site depositions within a single (~ 1kg) crystal





A Surprise: Pulse shape discrimination for high energy gammas

- Arrival time of charge spread out in PPC
- Pulse Shape Disc. is far superior & simpler than with other detector technologies (highly segmented N-type, Clover, standard Coax)